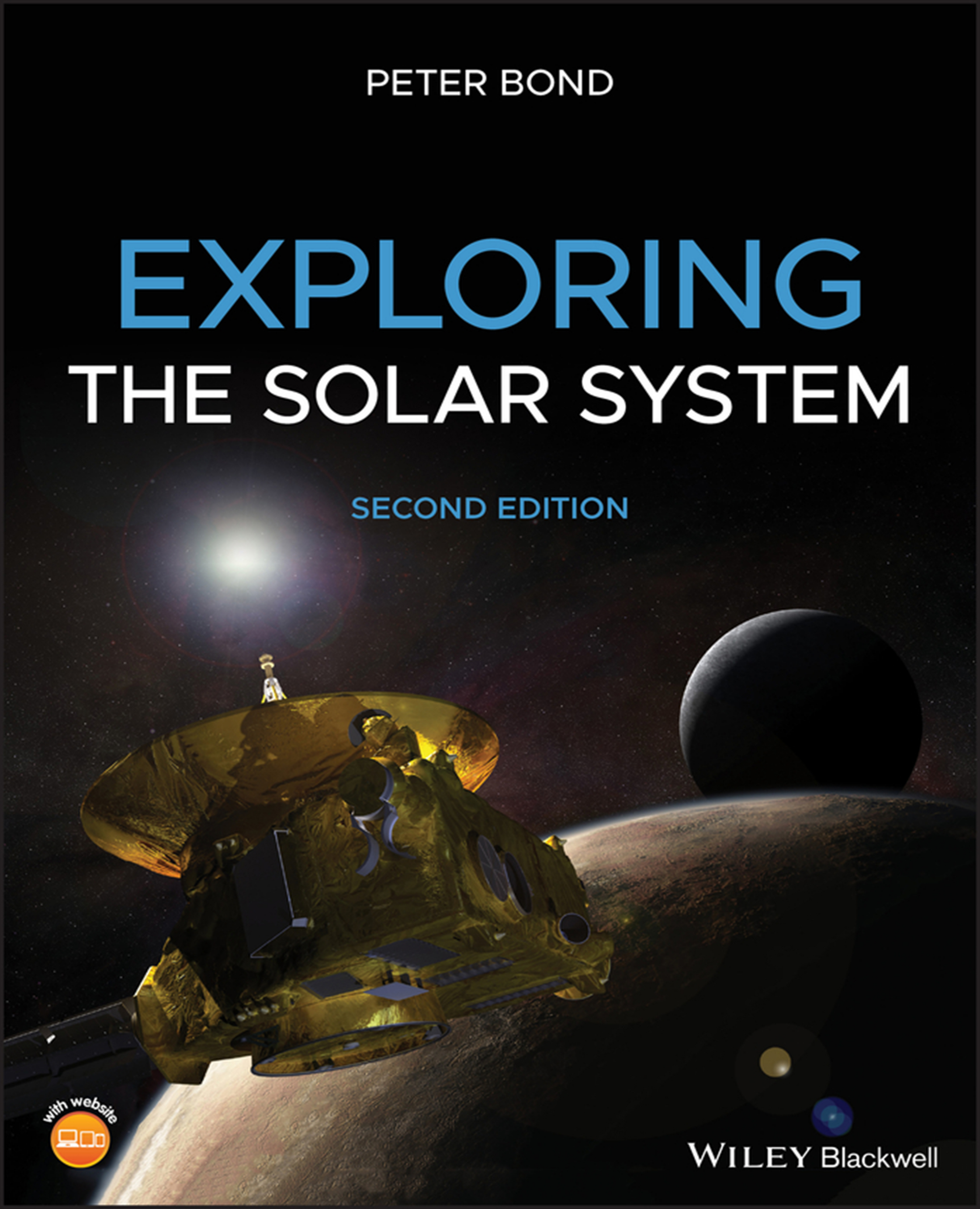
PETER BOND

EXPLORING THE SOLAR SYSTEM

SECOND EDITION



with website

WILEY Blackwell

Exploring the Solar System

Exploring the Solar System

Second Edition

Peter Bond

FRAS (Fellow of the Royal Astronomical Society)
FBIS (Fellow of the British Interplanetary Society)

WILEY Blackwell

This second edition first published 2020
© 2020 John Wiley & Sons Ltd.

Edition History
Wiley-Blackwell (1e, 2012)

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at http://www.wiley.com/go/permissions.

The right of Peter Bond to be identified as the author of this work has been asserted in accordance with law.

Registered Office(s)
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
9600 Garsington Road, Oxford, OX4 2DQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Limit of Liability/Disclaimer of Warranty

While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

Library of Congress Cataloging-in-Publication Data

Name: Bond, Peter, 1948- author.
Title: Exploring the solar system / Peter Bond, FRAS (Fellow of the Royal Astronomical Society), FBIS (Fellow of the British Interplanetary Society).
Description: Second edition. | Hoboken, NJ : Wiley-Blackwell, 2020. | Includes index.
Identifiers: LCCN 2019058265 (print) | LCCN 2019058266 (ebook) | ISBN 9781119384908 (paperback) | ISBN 9781119384892 (adobe pdf) | ISBN 9781119384915 (epub)
Subjects: LCSH: Solar system.
Classification: LCC QB501 .B69 2020 (print) | LCC QB501 (ebook) | DDC 523.2–dc23
LC record available at https://lccn.loc.gov/2019058265
LC ebook record available at https://lccn.loc.gov/2019058266

Cover Design: Wiley
Cover Image: © NASA

Set in 9/11.5pt, MinionPro by SPi Global, Chennai, India.

Printed in the UK by Bell & Bain Ltd, Glasgow.

10 9 8 7 6 5 4 3 2 1

Dedication

To my wife Edna, with whom I have travelled the rocky road of life. Also to the next generation of space travellers: Holly, Jack, Wren, Willow, Pearl, and Olive.

Conversion Table

The metric units used in this book can be converted to English units by using the approximate conversions given below:

Length

1 kilometer = 0.62 of a mile
1 meter = 39.37 inches
1 centimeter = 0.39 inches
1 millimeter = 0.039 inches

Area

1 sq. kilometer (km^2) = 0.04 sq. miles
1 sq. meter (m^2) = 1.2 sq. yards
1 sq. centimeter (cm^2) = 0.155 sq. inches

Temperature

To convert ° Celsius to ° Fahrenheit, multiply ° C by 1.8 and add 32

Speed

1000 km/h = 277.8 m/s = 621.37 mph

Volume

1 cubic cm (cm^3) = 0.061 cubic inches

Contents

Introduction to the First Edition

"We shall not cease from exploration and the end of all our exploring will be to arrive where we started... and know the place for the first time." – T.S. Elliot

This book is about a unique corner of the Universe, a small expanse of largely empty space that surrounds an ordinary star in the suburbs of the Milky Way galaxy. Known as the Solar System, this region is populated by the Sun, eight planets, dozens of satellites and dwarf planets, and a multitude of smaller objects.

Why is it important to explore and understand the Solar System? Because the third planet from the Sun is our home: Earth is the only place yet discovered where living organisms and intelligent life exist, or have ever existed. This unique "Goldilocks" world is the cradle of humankind, a fragile oasis in the vastness of space.

However, spaceship Earth is subject to many threats and stresses. Some are human-made, such as deforestation, atmospheric pollution, or emissions of ozone-destroying chemicals. Some are natural planetary processes, such as crustal movement and changing sea level. Others are external, including solar flares and marauding asteroids.

As news reports of natural disasters constantly remind us, Earth is an ever-changing world, subject to ice ages, hurricanes, earthquakes, volcanic eruptions, and devastating cosmic impacts. Since its birth some 4.5 billion years ago, the planet has endured all of these natural forces to evolve into the largely benign place we see today. If we can understand how this evolution occurred, then we will have a better chance of predicting how it will change in the future.

This is where studies of the Sun, planets, and other inhabitants of the Solar System come to the fore. Only by comparing and contrasting the evolution of these very different objects can we hope to understand the past, present, and future of our Earth.

This scientific endeavor has been made possible by the advent of the Space Age. During this great age of discovery, modern technology has enabled us to construct automated spacecraft and robots that can act as surrogate explorers, venturing forth into the vast, hostile ocean of space to seek out and study new worlds.

Over more than half a century, hundreds of robotic spacecraft have been sent from Earth to examine at close quarters all of the planets, and many other objects, in our Solar System. This book is based on the flood of data sent back by these probes, which has enabled scientists to assemble, piece by piece, a realistic picture of our Solar System. For the first time, human eyes have been able to see towering cliffs, dust devils, erupting volcanoes, dry river beds and ice formations on dozens of distant worlds, most of them totally alien to our experience here on Earth.

Many years ago, my imagination was captured by books that described the family of alien worlds that circle our Sun, although, at that time, most of the information available was pure speculation. I have been fascinated by the many and varied members of the Solar System ever since. It is my hope that readers of this book will be similarly fascinated and inspired.

Exploring the Solar System has been written as an introductory text book for undergraduate students with a modest background in science. However, it is also intended to inform and inspire anyone who looks up at the night sky and wishes to know more about the alien worlds that inhabit our corner of the Universe.

After an introductory chapter which provides an overview of the Solar System, the book sets out to systematically describe the main characteristics of each major planet and its retinue of satellites, as well as the smaller members of the Sun's retinue. The final chapter enables the reader to compare and contrast our Solar System with systems around distant stars, where huge numbers of strange and exotic exoplanets are now being discovered.

Questions at the end of each chapter have been added to help students to recognize and comprehend the main points of each chapter, and to compare each planetary system. Useful reference material is provided in the form of numerous appendices, an extensive reading list, and a comprehensive glossary.

This book would not have been possible without the support and encouragement of Ian Francis, Senior Commissioning Editor for Wiley-Blackwell, and Delia Sandford, the Managing Editor for this project. I am most grateful for their patience and forbearance as the book has edged towards completion.

My sincere thanks also go to Kelvin Matthews of Wiley-Blackwell, who has checked all of the illustrations, to the production team, especially Kathy Syplywczak, and to the various reviewers whose helpful comments and criticisms played such an important role in shaping the final text.

Much of the information in this book is based on original scientific papers, many of which are listed in the final pages. Numerous other sources – many now available on the Internet – were also used, including magazine articles, press releases, and other information provided by space agencies – particularly NASA - and universities. I am also very grateful to everyone who helped me to obtain, or provided me with, the spectacular images that illuminate this story of outreach and discovery.

Finally, I would like to thank my wife, Edna, who first encouraged me to describe and explain the wonders of our Solar System.

Peter Bond

Introduction to the Second Edition

Eight years after the first edition of this book was published, I am delighted to introduce a second edition. Although the structure of the book has not changed, the contents have been considerably revised and updated to reflect the flood of new information sent back by our robotic explorers.

The list of landmark events that have taken place since 2012 is impressive.

An entirely new book could be devoted to the discoveries Cassini made during its 13 years in orbit around beautiful Saturn. The completion of the Cassini mission in 2017 saw the first exploration of the gap between the inner ring and the planet. Other remarkable discoveries were made at cloud-shrouded Titan and on the icy geyser world of Enceladus, as well as the giant planet and its ever-changing rings.

The nuclear-powered New Horizons spacecraft revealed sheets of nitrogen ice, mountains, and deep valleys on distant Pluto and Charon, worlds that were previously believed to be inactive balls of ice. This success was followed by the first rendezvous with an even more remote Kuiper Belt object. Double-lobed 2014 MU69, a leftover remnant from the birth of the Solar System, seems to have been assembled during a low-speed collision.

More than 40 years after they left Earth, two more nuclear-powered craft, Voyagers 1 and 2, have left the Sun's realm and made the first crossings into interplanetary space.

The Juno orbiter is probing the invisible depths of Jupiter, providing new insights into the colorful cloud layers and deep interior of the gas giant.

Meanwhile, the MESSENGER spacecraft completed the first detailed reconnaissance of iron-hearted Mercury, whilst Japan's Akatsuki entered orbit around Venus and began imaging the super-rotating clouds.

Numerous robot explorers continue to study Mars from orbit and the surface, confirming the long-held beliefs that the Red Planet once supported rivers and large bodies of surface water – possible habitats for hardy, primitive organisms.

The smaller denizens of the Solar System have also attracted considerable attention. China achieved the first landing on the far side of the Moon, touching down on the unexplored South Pole-Aitken Basin.

Europe's Rosetta spacecraft made history when it flew alongside a comet for two years and released a lander onto its icy surface. Spacecraft from the U.S. and Japan have rendezvoused with small asteroids, revealing rocky rubble piles, and, following the success of Hayabusa 1, they are in the process of grabbing surface samples for analysis in labs back on Earth.

Following the release of huge amounts of new data from the armada of pioneering space missions, the scientific literature has expanded dramatically with the publication of new models and hypotheses – some contradictory, some revolutionary. Although planetary (and solar) science is in a continuous state of flux, I have tried to include many of these ground-breaking results and theories in this book, in an effort to showcase the latest research.

One of the most exciting research fields is the study of exoplanets, where space-based observatories, such as Kepler, and new ground-based instruments are opening new windows on an astonishing variety of alien worlds, many unlike anything that exists in our Solar System.

Only by studying distant worlds, whether in the Solar System or much further afield, can we hope to understand how our planetary system came about and how it may evolve in the future. There can be few more exciting areas of research, and I hope that the readers of this volume will be enthused by the evolving story of exploration described within these pages.

Peter Bond, September 2019

About the Companion Website

This book is accompanied by a companion website:

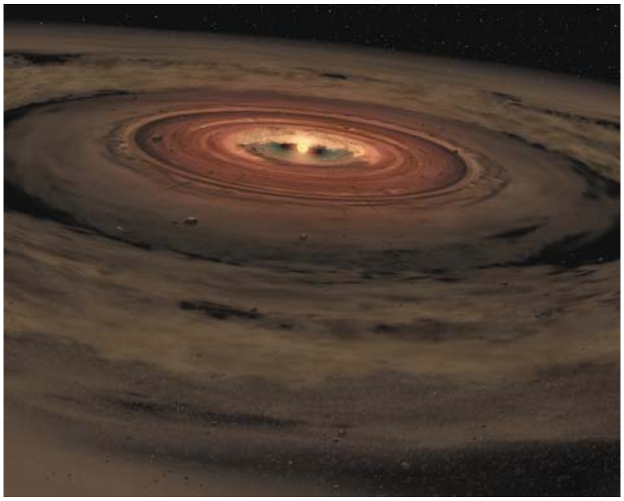
The URL is www.wiley.com/go/Bond-Solar-System2e

The website includes:

Figures and tables from the book

ONE

Beginnings



For millennia, people have studied the heavens and wondered about the nature and origins of the Sun, Moon, and planets. Indeed, Solar System studies dominated the field of astronomy until the introduction of powerful telescopes and advanced instruments in the 19th century. In the last 50 years, spacecraft have flown past or orbited all of the major planets and two dwarf planets, and landed on the Moon, Mars, Titan, a comet, and an asteroid. They have also brought back samples of Moon rock, comet and asteroid dust, as well as the solar wind. This era of robotic and human exploration has revolutionized scientists' knowledge of our corner of the Galaxy, and further astounding revelations are expected in the decades to come.

Wandering Stars

Since time immemorial, people have stared in wonder at the night sky. In previous millennia, when the darkness of the sky was not degraded by artificial lighting, it was easy to recognize how the stellar patterns drifted from horizon to horizon as the night progressed, and how they changed as the seasons passed.

However, in addition to the familiar, twinkling stars, observers noted seven objects that moved with varying speeds against the background of "fixed" stars.[1] In order of greatest apparent brightness, they were the Sun, Moon, Venus, Jupiter, Mars, Mercury, and Saturn. The ancient Greeks called them "planetes" ("wandering stars"), a designation we still use for all but the Sun and Moon.

For ancient astrologers and astronomers – the two disciplines were inextricably intertwined for many centuries – the most important of the wanderers were the Sun, which was responsible for daylight, and the Moon, which dominated the night. Both of these objects displayed visible disks and moved quite rapidly across the sky.

Careful study of their regular motions and apparitions enabled people to devise calendars and introduce convenient ways of measuring time. Thus, a year was the period before the Sun returned to the same place in the sky, while a month was the period that elapsed between each new or full Moon.

The other five planets were rather less noticeable, though each had its own peculiar characteristics. For example, Mercury and Venus never strayed far from the Sun in the twilight skies of morning or evening (Figure 1.1). The other three moved more slowly from constellation to constellation, sometimes describing loops in the sky as they appeared to temporarily reverse direction.

It was also evident that the seven planets often came together in the sky or even passed behind the Moon during occultations. They always remained within a narrow band on the sky, known as the zodiac (after the Greek word for "animal"). The Sun's annual path across the sky, called the ecliptic, ran along the center of this celestial highway. Clearly, the planes of the planets' orbits were closely aligned with each other.

The Earth-Centered Universe

Until the mid-16th century, it was accepted as an established fact by most civilizations that Earth lay at the center of the universe.[2] Like the axle of a wheel, everything else rotated around it.

---

[1] **For a time, the ancient Greeks thought there were nine planets. Venus was named both as the Evening Star (Hesperus) and the Morning Star (Phosphorus). Similarly, Mercury was thought to be two different planets – Lucifer and Hermes.**

[2] **A Sun-centered (heliocentric) model of the universe was proposed by the Greek astronomer Aristarchus in the 3rd century BCE, but it was not widely accepted.**

Exploring the Solar System, Second Edition. Peter Bond.

Companion Website: www.wiley.com/go/Bond-Solar-System2e

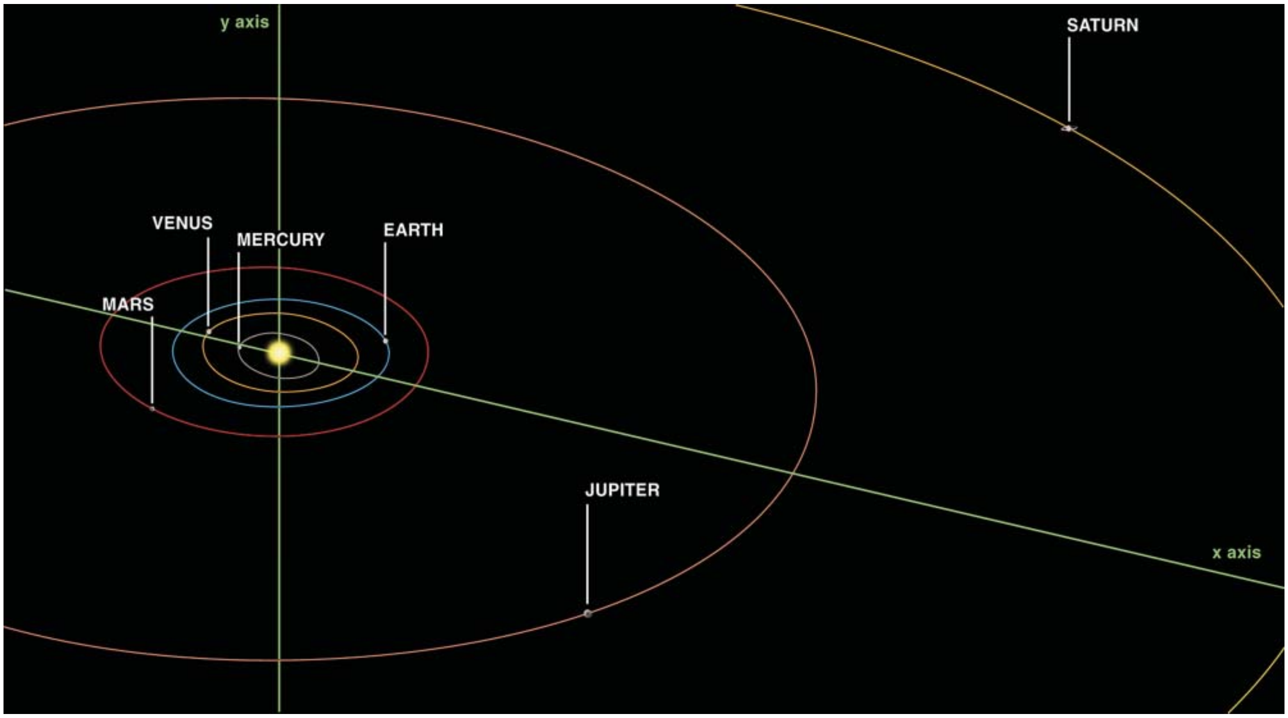


Figure 1.1 The relative sizes of the orbits of the "planets" visible to the naked eye and recognized by ancient astronomers. All the orbits are slightly elliptical and nearly in the same plane as Earth's orbit (the ecliptic). The diagram is from a view above the ecliptic plane and away from the perpendicular axis that goes through the Sun. (Lunar and Planetary Institute)

The reasons for this thinking seemed self evident. All the celestial objects, including the Sun, moved across the sky from east to west (with the occasional exception of a comet or shooting star). However, since no one experienced any of the sensations that would be expected if Earth was continually spinning, it seemed logical to believe that it was the heavens which were in motion around Earth.

According to this geocentric theory, the Sun, Moon, and planets were carried by invisible, crystalline spheres which were centered on the Earth. A much larger celestial sphere carried the fixed stars around the central Earth once every day.

Although early civilizations accepted the visual evidence that Earth is (more or less) flat, this idea was contradicted by several lines of evidence (see Chapter 3). For example, different star patterns or constellations are visible from different places. However, if Earth is flat, then the same constellations should be visible everywhere at a certain time.

One key piece of evidence was the curved outline of Earth's shadow as it drifted across the face of the full Moon during a total lunar eclipse. This was the case no matter where the observation was made or at what time it took place. Since only a spherical body can cast a round shadow in all orientations, it seemed clear that Earth was round.

Similarly, observations of a sailing ship disappearing over the horizon showed that, instead of simply becoming smaller and smaller, its hull disappeared from view before the sails and mast. This could only be explained on a curved ocean.

Measuring Distances and Sizes

One of the most fundamental problems facing early astronomers was the scale of the universe. How big were the Earth, Sun, and Moon, and how far away were they? It seemed evident that Earth was huge compared with every other object, and since it was the home of humanity, it was assumed that Earth was pre-eminent.

The question of the size of the spherical Earth was solved in the 3rd century BCE by Eratosthenes, who compared the length of shadows made at different locations at the time of the spring equinox (see Chapter 3). Some facts were also known about the relative sizes and distances of other objects.

Since its shadow easily covered the entire Moon during lunar eclipses, Earth had to be substantially larger than its satellite. During a solar eclipse, the Moon passed in front of the Sun, so the latter had to be further away. However, since their apparent sizes were identical, the Sun must be considerably larger than the Moon. Similarly, the Moon sometimes occulted or passed in front of stars and planets, so these, too, had to be much more remote.

Calculations by the Greek astronomers Aristarchus (c.310–c.230 BCE) and Hipparchus (c.190–120 BCE), based on the size of Earth's shadow, suggested that the Moon's diameter is about one third that of Earth and that its distance is nearly 59 times Earth's radius. This established the scale of the Earth–Moon system with a fair degree of accuracy. However, their simple geometric methods grossly underestimated the Sun's distance.

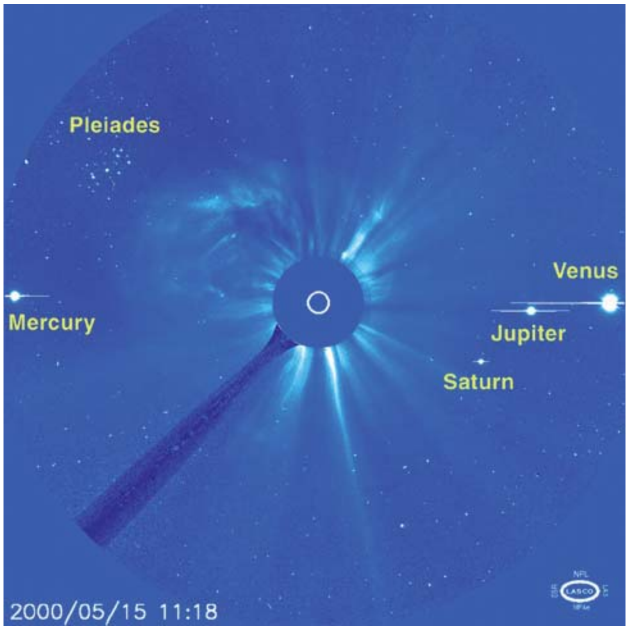


Figure 1.2 All the major planets follow orbits that lie within 8° of the Sun's path across the sky – the ecliptic. This narrow celestial belt is known as the zodiac. In this image from the SOHO spacecraft, four planets appear close to the Sun (whose light is blocked by an occulting disk). Also in view are some background "fixed" stars, including the Pleiades cluster. (ESA-NASA)

Determination of the planetary distances remained problematic for a long time. It soon became clear to observers in the classical world that some planets move more slowly through the constellations of the night sky. Since a slow-moving planet such as Saturn was also fainter than the faster-moving objects, Mars and Jupiter, it seemed logical that Saturn was further away from Earth.

It was also clear that the Sun, Moon, and planets did not move at uniform speeds or follow simple curved paths across the sky. One of the most difficult observations to explain was an occasional "loop" in the motions of the more distant planets. This occurred when Mars, Jupiter, and Saturn were shining brightly around midnight (Figure 1.3 and Box 1.1). At such times, the planet's nightly eastward ("prograde") motion would gradually come to a stop. It would then reverse direction toward the west, becoming "retrograde," before resuming its general movement toward the east.

The explanation for this motion had to wait until astronomers realized that the Sun was at the center of the planetary system, and that Earth orbited the Sun (see The Central Sun). The loops could then be accounted for by Earth traveling along a smaller orbit so that it would catch up with, then overtake, the outer planets (see Figure 1.3) – like an athlete on an inside track.

Accurate calculations of planetary distances also had to wait until the 17th century, when observers were able to measure angular distances with reasonable accuracy. The basic geometrical method they used was called parallax (Figure 1.4).

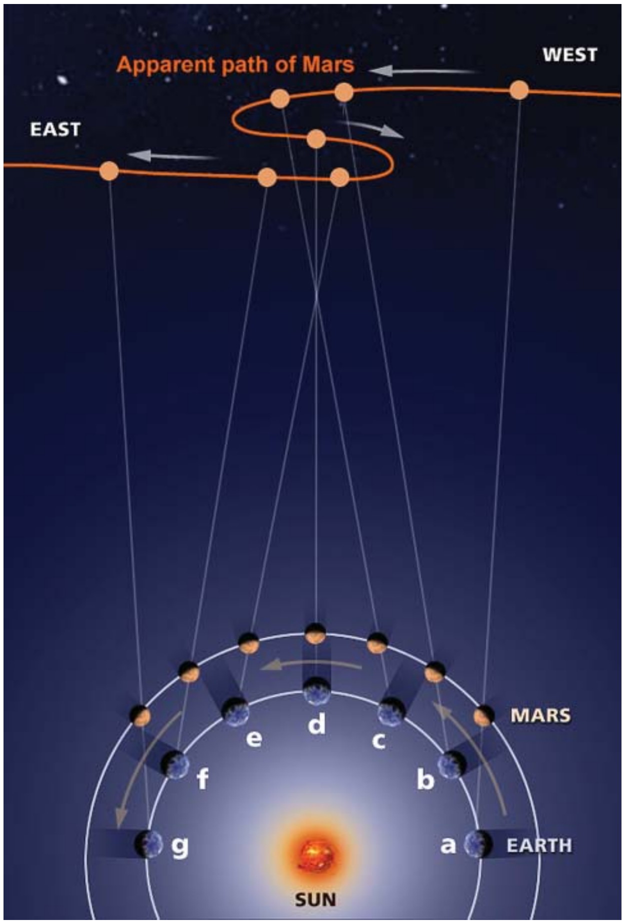


Figure 1.3 The apparent retrograde ("backward" or east–west) motions of Mars, Jupiter, and Saturn are now known to be caused by the relative orbital movement of the planets and Earth. Since Earth moves faster along its orbit than the more distant planets, it overtakes them on the inside track. As Earth approaches and passes Mars, the slower moving outer planet appears to move backward for a few months against the backcloth of "fixed" stars. (After NASA)

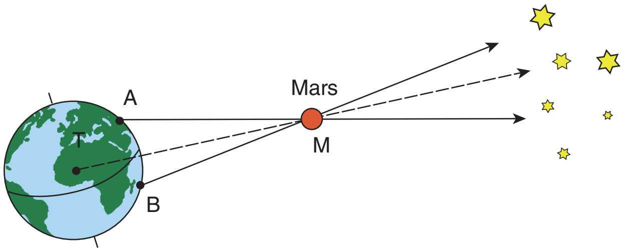


Figure 1.4 The distance of a planet such as Mars can be calculated by measuring its angle of sight – its location against the background of fixed stars – from two or more places on Earth. If the length of the baseline (e.g. the distance between two viewing sites, A-B) is known, the distance can be found by using simple trigonometry. (ESO)

This involved measurement of the apparent shift in position of an object when viewed from two different locations. To illustrate this, hold one finger upright in front of your nose and close first one eye and then the other. The finger seems to shift position against the background, although it is, of course, stationary. When the finger is moved closer, the shift appears larger, and vice versa.

Astronomers realized that, if a parallax shift in a planet's position could be measured from two widely separated locations, then its distance could be calculated. This method was first used by a French astronomer, Jean Richer, working in Cayenne (French Guiana), together with Giovanni Domenico Cassini and Jean Picard in Paris. They made simultaneous parallax observations of Mars during its closest approach in 1671, using the recently invented pendulum clocks to ensure that the measurements were made at precisely the same moment.[3]

Cassini's calculations led to a value of about 140 million km for the astronomical unit (AU) – the mean Sun–Earth distance. Now that this distance was known with reasonable accuracy, Kepler's third law (see Box 1.2) could be used to calculate the distances of the Sun and planets for the first time.

During the 18th century a great deal of time, money, and effort was spent in attempting to refine these figures. One method was to observe rare transits of Venus across the face of the Sun from many different locations. The most famous transit observations took place in 1761 and 1769 when the British explorer, Captain James Cook, sailed to the Pacific as part of an army of 150 observers scattered across the globe, but these gave very inaccurate results (see Chapter 6).

More successful was the worldwide effort to determine the parallax of the asteroid Eros when it passed close to Earth in 1931. Highly accurate measurements were possible since Eros has no atmosphere and appears as a mere point of light in even the largest telescopes. The value of the astronomical unit turned out to be 149.6 million km.

Since then, more sophisticated techniques have been introduced to refine the scale of the Solar System. One of the most successful is radar, when radio signals are reflected from the surfaces of distant objects (see Chapters 5, 6, and 13). Since the velocity of these microwaves is known and the time taken between emission and reception can be measured to a fraction of a second, the distance can be readily calculated. (Radar has also revealed the sizes and shapes of hundreds of asteroids.) A similar technique used to calculate changes in the Earth–Moon distance involves the use of laser pulses bounced off special reflectors left on the lunar surface.

Once an object's distance is accurately known, the diameter can be determined from its apparent angular size, as seen in a telescope. Unfortunately, this is very difficult for the smaller or more distant members of the Solar System, particularly if their albedo, or surface reflectivity, is uncertain.

In general, the larger an object, the more light its surface reflects. However, some objects are much better mirrors than others. A small, reflective object can have the same apparent brightness as a large, dark object. For example, observations of some Kuiper Belt objects, beyond the orbit of Pluto, indicate that their albedos are greater than previously believed. Since they are more reflective than anticipated, astronomers have revised their diameters downwards.

Another method, involving the occultation of a star by a planet or other object, is especially valuable in relation to objects which are normally difficult to observe. The object's diameter is calculated from the length of time during which it hides the star from view. This technique has been used to discover the rings of Uranus and Neptune, and to study Pluto's largest moon, Charon, for example. It is also invaluable for the detection and observation of exoplanets in orbit around distant stars (see Chapter 14). Unfortunately, if the object possesses a dense, cloudy atmosphere, the occultation only gives the diameter at the cloud tops.

The Central Sun

The difficult task of breaking with tradition and accepting the Sun as the center of the universe began with a Polish priest and astronomer named Nicolaus Copernicus (1473–1543). He decided that the only way to make sense of the planetary orbits was to relegate Earth to the status of a planet that orbited the Sun. The movement of the stars across the sky was then explained by the rotation of the spherical Earth, while the calendar of seasons and changing constellations in the heavens were accounted for by its year-long journey around the Sun.

Copernicus' most significant work, called *De Revolutionibus Orbium Celestium* (Concerning the Revolutions of the Celestial Spheres), was published shortly before his death. Curiously, this did not provoke a violent reaction by the establishment of the day, nor did it immediately lead to any major upheaval in scientific thought. Lacking enough evidence to swing the argument one way or the other, the great minds of the day were faced with an impasse.

Half a century passed before the interventions of two great scholars swung the argument in favor of Copernicus' heliocentric theory. The first breakthrough was made in 1609 by a young German named Johannes Kepler. By one of those strange twists of irony, Kepler was a pupil of Tycho Brahe, one of the leading opponents of the Copernican order. Given the unenviable task of finding an explanation for the retrograde motion of Mars (see Figure 1.3), Kepler was able to draw upon the excellent observational data recorded by his employer.

Brahe died in 1601, but Kepler continued to laboriously examine the problem before finally arriving at his eureka moment. The planetary orbits, he declared, were not circles but ellipses (regular oval shapes).[4] Within a short time, Kepler was able to draw up the first two laws of planetary motion (see Box 1.2). His third, and probably most important law, followed in 1619.

As a result, the relative distance of each planet from the Sun could be calculated accurately. Saturn, the most remote planet known at the time, turned out to be nearly 10 times further from the Sun than Earth. Since the actual distances remained unknown, the standard unit of measurement became the astronomical unit,

[3] **A by-product of this experiment was the discovery that a pendulum swung more slowly at Cayenne than at Paris, showing that gravity is slightly weaker at the equator. Isaac Newton later used this result to show that Earth's diameter is greatest at the equator.**

[4] **Kepler's task was made slightly easier by the fact that, of the five known planets, only Mercury followed a more elliptical path than Mars.**

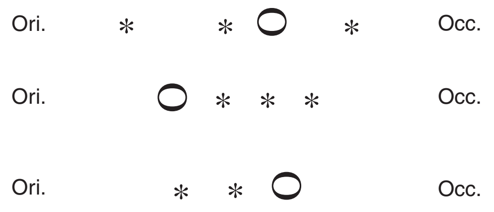


Figure 1.5 In January 1610, Galileo Galilei used his simple refracting telescope to discover three "stars" aligned on either side of Jupiter. Over a period of several weeks, a fourth "star" appeared. As they shifted positions, Galileo correctly deduced that these were satellites. *Occ.* is the Latin abbreviation for "west" and *Ori.* stands for "east." (NASA)

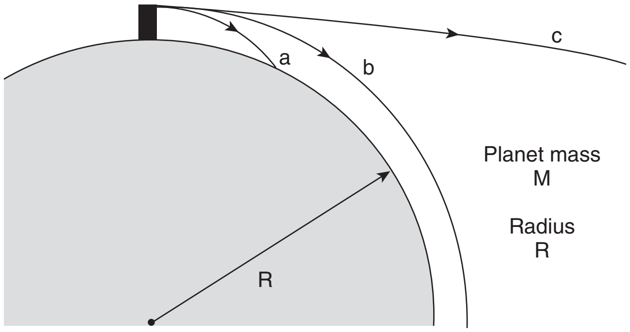


Figure 1.6 (a) If a spacecraft does not accelerate to orbital velocity, it will fall back to the planet's surface. (b) If it reaches orbital velocity, it will remain in a closed path (orbit) around the planet under free fall conditions. (c) If the spacecraft reaches escape velocity, it will be able to break free from the planet's gravitational pull and travel to another planet. The same rules apply to planets and spacecraft in orbit around the Sun. (NASA)

so Saturn's distance from the Sun was about 10 astronomical units or 10 AU.

In the same year that Kepler discovered elliptical orbits, an Italian scientist named Galileo Galilei made a simple refracting telescope, comprising two lenses at either end of a narrow tube, and began to study the heavens. Within a short time, despite the small magnification offered by his "optic tube," he had obtained visual evidence to support the theories of Copernicus and Kepler. Galileo became the first person in history to see the phases of Venus caused by its movement around the Sun. He also observed mountains and craters on the Moon, and saw the planets as disks, rather than points of light.

Most significant of all was his discovery of four star-like objects close to Jupiter (Figure 1.5). By watching their daily motions, he was able to calculate their orbital periods and show that they were Jovian moons (see Chapter 7). The discovery of the first planetary satellites (other than the Moon) supported theories that Earth was not at the center of the universe and confirmed that everything did not revolve around our world.

Galileo's discoveries caused a sensation, although the leaders of the Roman Catholic Church obstinately continued to support a geocentric universe. In 1633, Galileo was brought before the Inquisition and forced to recant under threat of torture.

Newton and Gravity

The next challenge was to find an explanation for Kepler's laws. Although Galileo conducted numerous experiments into the effects of gravity, he did not realize the full significance of his discoveries. This was left to an Englishman, Isaac Newton, who was born in 1642, the year that Galileo died.

One anecdote attributes Newton's discovery of universal gravitation to him observing an apple falling from a tree. Whatever the truth, by 1684 Newton was able to explain planetary motions. His law of gravitation stated that all objects attract each other, and that the strength of this gravitational attraction is proportional to their mass (see Chapter 8).

Clearly, since the Sun has nearly all the mass in the Solar System, it should pull all of the other bodies into it. Newton explained that this did not happen because their orbital velocities are just sufficient to counteract the Sun's gravity. The result is that the planets fall towards the Sun in such a way that the curve of their fall takes them completely around it (Figure 1.6). This is sometimes known as free fall. (This same explanation, of course, applies to artificial satellites.)

Newton's law also stated that the strength of gravitational attraction decreases with distance. For example, if planet A is twice as far from the Sun as planet B, then the gravitational force exerted by the Sun on planet A is one quarter that exerted on planet B.

In practical terms, this means that a satellite in low Earth orbit must travel at 8 km/s, whereas the Moon only has to circle the Earth at 1 km/s in order to avoid crashing into our planet. Similarly, planets further from the Sun are able to move more slowly around their orbits than those in the inner Solar System. Newton's law also explained why a planet's orbital speed increased as it approached perihelion (closest point to the Sun) and slowed near aphelion (furthest point from the Sun).

From this time on the orbital mechanics of the Solar System were very well understood. With the exception of Mercury, whose orbital motion refused to obey Newton's law (see Chapter 5), the only significant problems involved minor variations in orbits caused by gravitational interactions between the planets, particularly those involving massive Jupiter. Careful study of unexpected changes in the orbital velocity of Uranus may even have enabled the position of an unknown planet, Neptune, to be successfully calculated (see Chapter 11) – although there are those who consider the discovery to be pure chance.

What Is A Planet?

In the ancient world, astronomers counted eight planets. When the Sun, Earth, and Moon are removed from their list, the number of planets visible to the naked eye is reduced to five: Mercury, Venus, Mars, Jupiter, and Saturn.

Box 1.1 Orbits

The direction a spacecraft or other body travels in orbit can be prograde, when a satellite moves in the same direction as the planet (or star) rotates, or retrograde, when it goes in a direction opposite to the planet's (or star's) rotation. All of the planets in the Solar System orbit the Sun in a prograde direction – west to east or counterclockwise as observed from above the Sun's north pole. However, many comets and some satellites move in a retrograde (clockwise) direction.

Various technical terms are used to describe the characteristics of these orbits. The time an object takes to complete one orbit is known as the orbital period. The closest point of an orbit has the prefix "peri" – hence perigee for a satellite of the Earth and perihelion for an object orbiting the Sun. (Helios = Sun.) The furthest point in an orbit has the prefix "ap" – as in apogee and aphelion.

The plane of Earth's orbit around the Sun is called the ecliptic. The orbits of the other planets, comets, and asteroids are tilted to this plane. The angle of the tilt is the orbital inclination. The inclination of a satellite's orbit is measured with respect to the planet's equator. Hence, an orbit directly above the equator has an inclination of 0°, while one passing over a planet's poles has an inclination of 90°.

A planet, asteroid, or comet crosses the ecliptic twice during each orbit of the Sun. The points where an orbit crosses a plane are known as nodes. When an orbiting body crosses the ecliptic plane going north, the node is referred to as the ascending node. Going south, it is the descending node. The line that joins the ascending node and the descending node of an orbit is called the line of nodes.

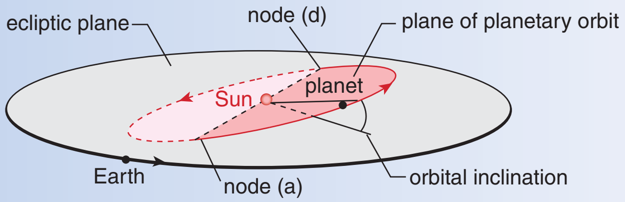


Figure 1.7 Some important characteristics of a planet's orbit. Here the planet is inferior, i.e. closer to the Sun than Earth. Its orbit is inclined to the ecliptic – the plane of Earth's orbit. The planet's orbit crosses the ecliptic at two nodes – the ascending node (a) and the descending node (d). (Peter Bond, after Open University)

One of the most important orbital, or Keplerian, elements, is the semi-major axis, the average distance of an object from its primary (planet or Sun). The shape of the orbit is described by its eccentricity, measured as a number between zero and 1. An eccentricity of zero indicates a circular orbit. A parabola has an eccentricity of 1.

With the invention of the telescope, the possibility arose of finding fainter, more remote planets. The first newcomer, Uranus, was discovered far beyond the orbit of Saturn by William Herschel in 1781. The list was further increased in 1801, when Giuseppe Piazzi found Ceres in the gap between the orbits of Jupiter and Mars. Pallas, Juno, and Vesta – objects in similar orbits to Ceres – were discovered between 1802 and 1807. Since they were clearly much smaller and less substantial than the other planets, they were soon downgraded to "minor planets" or "asteroids" (star-like objects).

Almost 40 years passed before the eighth planet, Neptune, was discovered by Johann Galle and Heinrich D'Arrest. However, neither Uranus nor Neptune seemed to be following its expected path, suggesting that an even more distant planet might be influencing the movements of its neighbors. The search for this world concluded in 1930 when Clyde Tombaugh observed the tiny image of Pluto on a photographic plate.

For many years, it was generally accepted that there were nine planets, despite growing concerns that Pluto seemed to be too small and lacking in mass to deserve this title. The crunch came in 2003, when Mike Brown discovered 2003 UB313 (now named Eris), an object that is comparable in size to Pluto. With the introduction of ever more sensitive detectors, it seemed likely that there would soon be dozens of Pluto-sized planets.

Aware that there was no generally accepted definition of the term "planet" and faced with a fierce debate over whether Pluto should be demoted, members of the International Astronomical Union gathered in Prague for the 2006 General Assembly.

After a lengthy discussion, they agreed to define a planet as a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared other objects from the neighborhood of its orbit.

Based on these criteria, the Solar System now consists of eight planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. A new distinct class of objects called "dwarf planets" was also introduced (Figure 1.8). To be classified as a dwarf planet, an object must orbit the Sun and have a nearly round shape. The first dwarf planets to be announced were Ceres (the largest asteroid), Pluto, and Eris, followed by three more. Many others are expected to be discovered in the future.

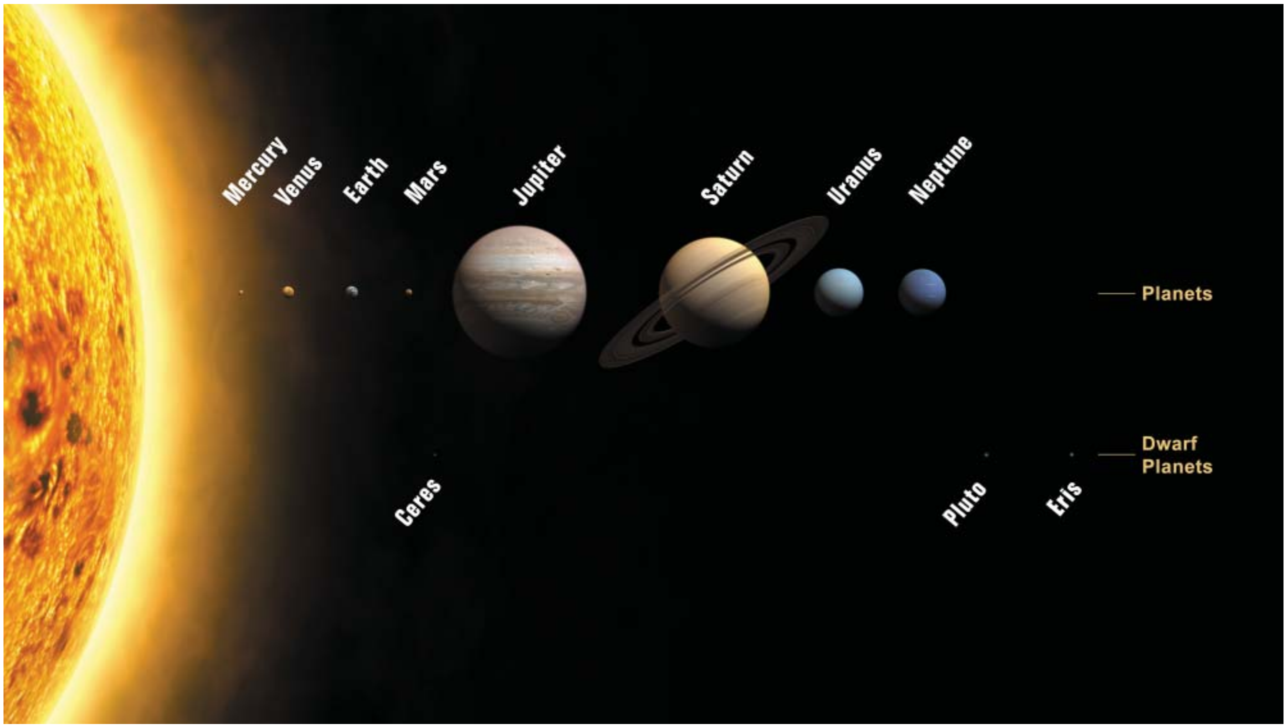


Figure 1.8 In the "new" Solar System, as defined by the International Astronomical Union in 2006, there are eight planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune (shown in order of their distance from the Sun). A new, distinct class of objects called "dwarf planets" includes the largest asteroid, Ceres, and the two largest known Kuiper Belt objects, Pluto and Eris. The relative sizes of the planets and the Sun are shown. Jupiter's diameter is about 11 times that of Earth, and the Sun's diameter is about 10 times that of Jupiter. The distances of the planets are not shown to scale. (IAU)

This decision has not met with universal approval. One common criticism relates to what exactly is meant by a planet "clearing its neighborhood." For example, critics argue that Neptune is accepted as a planet, even though many Kuiper Belt objects (including Pluto) cross its orbit. Perhaps, they suggest, it would be more appropriate to use size as a criterion, particularly bearing in mind the diameters of objects that are large enough for gravity to dominate structural strength. There is also some discomfiture with defining Ceres – the largest of the asteroids – as a dwarf planet.

Another complication arises when the current definition is extended to extrasolar planets, i.e. planets orbiting other stars (see Chapter 14). Size is not a useful factor, since many of these planets are similar in size and mass to small, cool "failed stars" known as brown dwarfs.

Instead, astronomers attempt to distinguish between a giant extrasolar planet and a brown dwarf by determining how they were born. A star is formed during the gravitational collapse of a gaseous nebula, whereas a planet is the product of collisions and accretion (snowball-like growth) between particles in a disk of gas and dust around a central star. Even so, this method of differentiation is difficult to apply, especially in the case of planet-sized objects that have been flung into interstellar space and no longer orbit any star.

The Solar System

50 years ago, the population of the Solar System included one central star, nine planets, 31 satellites, and thousands of comets and asteroids. However, since the arrival of the Space Age and the development of ever more sensitive ground-based instruments, the inventory of objects has swollen remarkably.

Today, the astronomical community recognizes eight planets and five dwarf planets, the tally of planetary satellites has passed 150, and the number of identified small objects is climbing rapidly as increasingly sensitive searches discover thousands of Sun-grazing comets and icy Kuiper Belt objects that orbit beyond Neptune.

In terms of numbers, the Solar System is dominated by debris, in the form of comets, asteroids, meteorites, and dust. These are the leftovers from the formation of the planets, 4.5 billion years ago. The main asteroid belt, between Mars and Jupiter, is populated by millions of rocky objects that are shepherded by the powerful gravity of the nearby gas giant. They are thought to represent planetesimals – small planetary building blocks – that were unable to accrete due to the gravitational interference of Jupiter.

Beyond the orbit of Neptune are two more swarms of small objects, this time largely made of ice (Figure 1.9 and Figure 1.10). The inner region, known as the Kuiper Belt, is where short-period

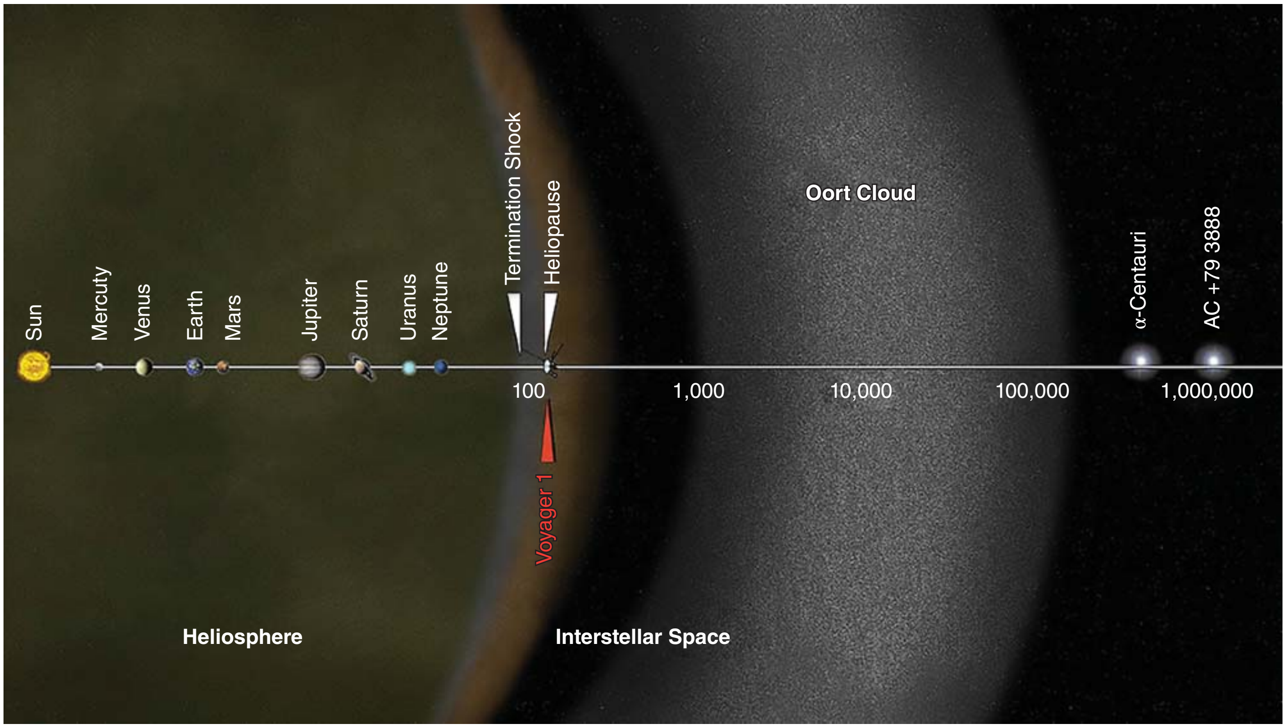


Figure 1.9 The size of the Solar System. The scale bar is in astronomical units, with each marked distance beyond 1 AU representing 10 times the previous distance. One AU is the distance from the Sun to the Earth, which is about 150 million km. The Kuiper Belt, which extends beyond Neptune from about 30 to 55 AU, is not shown. Two distant stars are also shown (right). (NASA/JPL-Caltech)

comets originate. Pluto and Eris are the largest known inhabitants. The orbital periods of Kuiper Belt objects range from 200–400 years for objects such as Pluto to 1,000 years or longer for those which follow very elliptical orbits that take them far from the Sun.

The Kuiper Belt poses a serious challenge for theories of planet formation, since it contains less than 1% of the mass of the protosolar nebula. If the Kuiper Belt objects formed like the terrestrial planets, growing by accumulating smaller objects as they orbit the Sun, the shortage of local building material means it would take longer than the age of the Solar System to make one KBO!

Even further out – indeed, so far that none of the objects have ever been observed in situ – is the postulated Oort Cloud, the home of most long-period comets.

The basic characteristics of the Solar System are straightforward to describe. Close to the Sun, where temperatures are higher, there are four quite small, but dense, "terrestrial" planets that are composed largely of rock (Figure 1.11 and Table 1.1). Beyond Mars, where temperatures are always well below zero, is the realm of the gas giants, Jupiter and Saturn, and the ice giants, Uranus and Neptune.

As noted above, the orbits of the major planets are approximately circular, and close to the ecliptic plane. All of the planets and main belt asteroids circle the Sun in the same direction – counterclockwise as seen from above the Sun's north pole. This is also the direction of the Sun's rotation. However, the beautiful symmetry breaks down when it comes to the smaller members of the Solar System. Comets can arrive from any direction, and the orbits of the Kuiper Belt objects have no particular orientation, suggesting that there is a spherical swarm of these objects surrounding the Sun and major planets.

Of the four inner planets, Venus and Earth both possess dense atmospheres – though they are very different in nature – while Mercury is too lightweight to have retained a substantial gaseous envelope. Whereas the most common gas on both Venus and Mars is carbon dioxide, Earth is something of an oddball, with an atmosphere dominated by nitrogen and oxygen. This latter gas can be accounted for by the fact that Earth is – as far as we know – the only abode of life in our Solar System, and it is those life forms that pump oxygen into the air. Satellites are rare: Earth is orbited by the Moon, while Mars has two small companions that are generally considered to be captured asteroids.

As their name suggests, the gas and ice giants are characterized by their large size – tens to thousands of times bigger than Earth – and low bulk densities which can be accounted for by the dominance of hydrogen and helium in their interiors. All four of the giants have ring systems composed of dust, ice, and rocky debris, and their gravitational influence is such that they retain dozens of satellites – most of them captured billions of years ago.

Since they are relatively close to the Sun, all the terrestrial planets have high orbital velocities with periods of less than two Earth years (see Box 1.2: Kepler's Third Law). In contrast, their axial rotations are slow and their axial inclinations are very different.

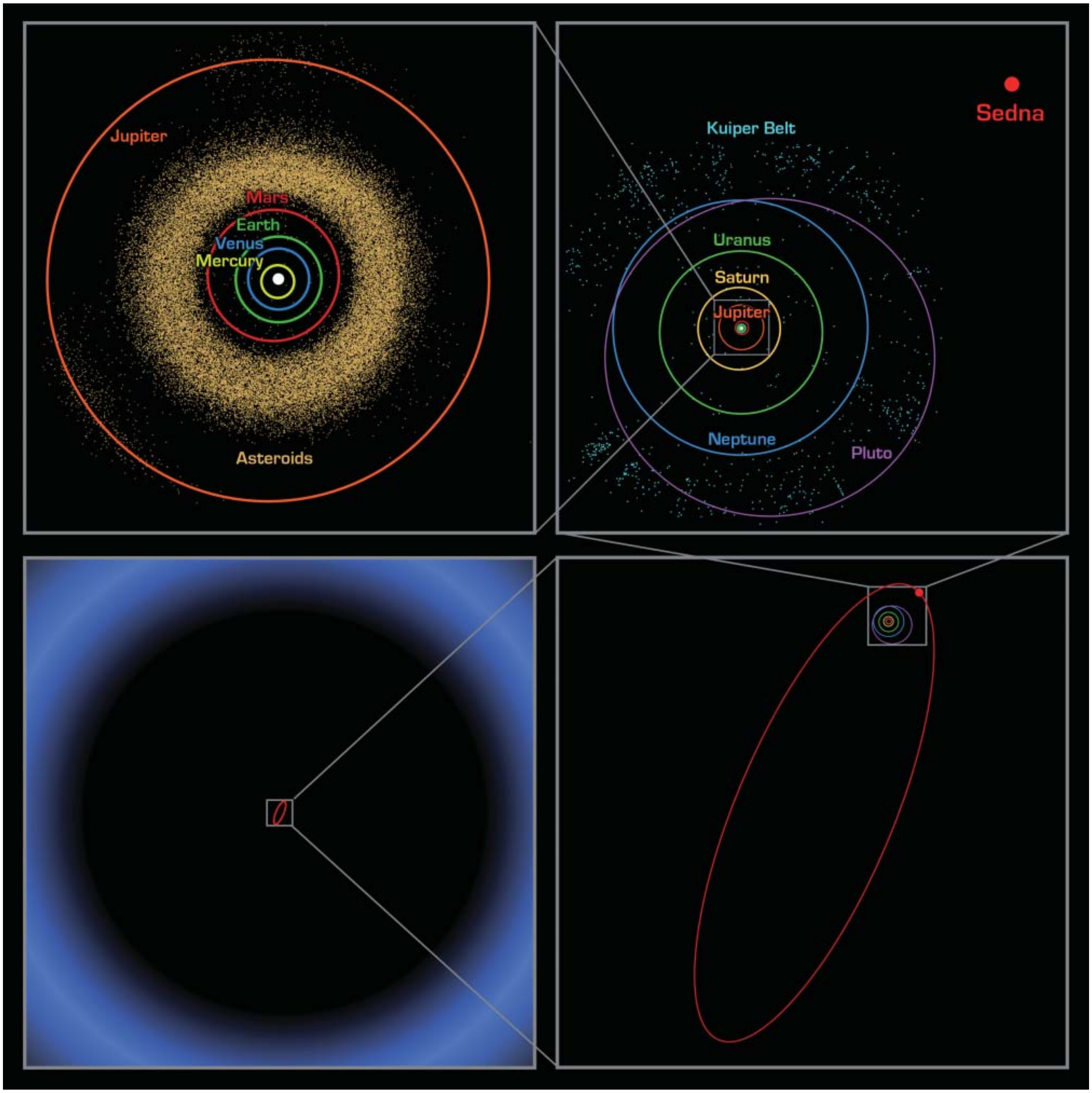


Figure 1.10 These four panels show the scale of the Solar System as we know it today. At top left are the orbits of the inner planets and the main asteroid belt. Top right shows the orbits of the outer planets and the Kuiper Belt. Lower right shows the orbit and current location of Sedna, one of the most distant known objects in the Solar System. Lower left shows that even Sedna's highly elliptical orbit, which takes it nearly 1,000 AU from the Sun, lies well inside the proposed Oort Cloud (shown in blue). This spherical cloud contains millions of icy bodies orbiting at the limits of the Sun's gravitational pull. (NASA/JPL/R. Hurt, SSC-Caltech)

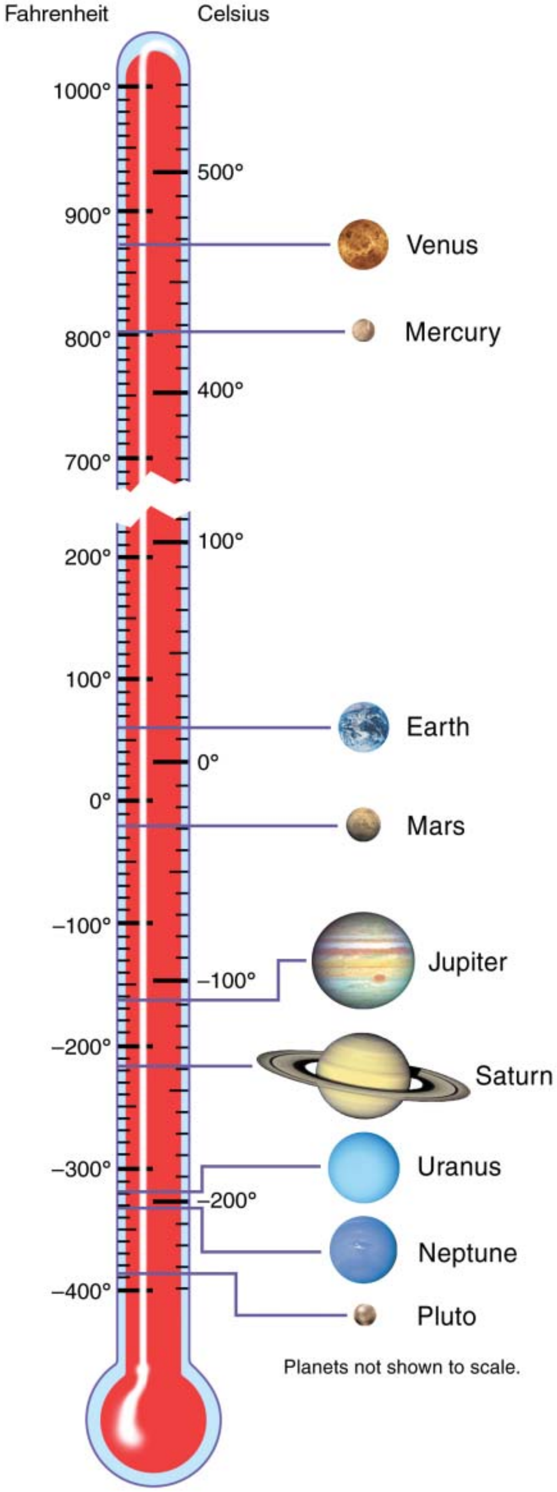


Figure 1.11 In general, a planet's surface temperature decreases with its distance from the Sun. Venus is the exception, since its dense carbon dioxide atmosphere traps infrared radiation. The runaway greenhouse effect raises its surface temperature to 467°C. Mercury's slow rotation and thin atmosphere result in the night-side temperature being more than 500°C colder than the dayside temperature shown above. Temperatures for Jupiter, Saturn, Uranus, and Neptune are shown for an altitude in the atmosphere where pressure is equal to that at sea level on Earth. Earth lies in the center of the "habitable zone," where water can exist as a liquid and conditions are favorable to life. (NASA / Lunar and Planetary Institute)

Table 1.1
The Planets: Relationship Between Solar Distance and Mean Density

Planet	Distance from Sun (AU)	Mean Density (g/cm^3)
Mercury	0.3871	5.43
Venus	0.7233	5.24
Earth	1.0	5.52
Mars	1.5237	3.91
Jupiter	5.2028	1.33
Saturn	9.5388	0.69
Uranus	19.1914	1.29
Neptune	30.0611	1.64

Mercury's axis is almost at right angles to its orbit. It takes 58 days to rotate once, or about two-thirds of the time it takes to orbit the Sun. Venus resembles a top that has been knocked completely upside down. As a result, it rotates in a retrograde direction that takes 243 Earth days, longer than its orbital period. Earth and Mars have very similar days and seasons – at least in the present epoch – since their sidereal periods of axial rotation are both around 24 hours and both axes are inclined about 24–25° to their orbits (Figure 1.12).

The motions of the outer planets are very different. Their large distances from the Sun require modest velocities to maintain their orbits. Orbital periods range from almost 12 years for Jupiter to about 165 years for Neptune. However, despite their swollen spheres, they all spin much faster on their axes than their terrestrial siblings, with sidereal periods in the range of 10–20 hours.[5] However, there is considerable variation in their axial tilts. Jupiter is almost upright, Saturn and Neptune are inclined more than Earth and Mars, while Uranus spins on its side so that the polar regions alternately point toward or away from the Sun.

The orbits and axial inclinations of the planets (and satellites) are not fixed, e.g. the axial tilt of Mars changes dramatically over millions of years.

The Birth of the Solar System

The Sun, which contains over 99% of the Solar System's mass, completes one rotation in about 24 days. In contrast, the largest planets, Jupiter and Saturn, rotate once in about 10 hours. When combined with their orbital motion, it turns out that Jupiter accounts for some 60% of the Solar System's angular momentum, with another 25% accounted for by Saturn. This compares with about 2% for the sluggardly Sun.

Any theory of cosmogony that attempts to account for the formation of the Solar System must take into account the angular momentum of the Solar System objects, as well as the facts that all of the planets travel in the same direction and more or less in the same plane. The obvious conclusion is that they all formed in the same manner and at about the same time.

Scientists have usually considered two main possibilities: the planets were either created by material derived from the Sun or a nearby companion star, or they formed from a cloud of diffuse matter that surrounded the Sun. However, theorists have struggled for centuries to match the hypotheses to the known facts, in order to choose between them.

One of the earliest, and most successful, attempts to explain how the Solar System came about was the nebular hypothesis – the idea that the Sun and planets formed from a vast, slowly rotating disk of gas and dust. A modified version of this hypothesis is the generally accepted explanation today.

Some of the key evidence comes from modern observations of distant star systems. Today, spaceborne telescopes can peer into the hearts of giant molecular clouds, such as the Orion Nebula, and search for young, Sun-like stars that replicate the conditions that prevailed in our Solar System some 4.6 billion years ago.

These observations show that so-called protoplanetary disks, or proplyds, exist around most very young stars – those less than 10 million years old (Figure 1.16). Many of the disks are larger than our Solar System. Observations of slightly older stars show how these disks evolve as time goes by, with the formation of swarms of rocky and icy debris and gaps in the clouds created by fledgling planets.

As currently envisaged, the Solar System began with the collapse of a cloud of interstellar gas. The trigger for this collapse may have been the passage of an externally generated shock wave from a supernova explosion, density waves passing through the galaxy, or a major reduction in the cloud's magnetic field or temperature.

The first of these explanations is the prime candidate, since many stars form in clusters within clouds containing thousands of solar masses of material. When the giant stars of the cluster run through their short life spans, they are likely to produce a series of supernovas, preceded by powerful stellar winds.

Evidence from meteorites and dynamical modeling of supernova shock wave propagation into giant molecular clouds indicate that a supernova explosion compressed part of a cloud, causing this region to collapse. The shock wave would also have injected material from the exploding star into the solar nebula. Scientists have detected evidence of this material in the form of the decay products from radioactive isotopes, particularly iron-60. These are found in primitive meteorites and can only form in the giant stars that end their lives as supernovas.

Over millions of years, the original cloud may be broken up into smaller fragments, each mixed with heavier elements from the dying stars, as well as the ubiquitous hydrogen and helium gas. Once a fragment reaches a critical density, it is able to overcome the forces associated with gas pressure and begins to collapse under its own gravity.

The contracting cloud begins to rotate, slowly at first, then faster and faster – rather like when an ice skater pulls in his arms. Since material falling from above and below the plane of rotation collides at the mid-plane of the collapsing cloud, its motion is cancelled out. The cloud begins to flatten into a disk, with a bulge at the center where the protostar is forming. The disk was probably thicker

---

[5] **The sidereal rotation period is the time a planet takes to spin once on its axis, with respect to a particular background star.**

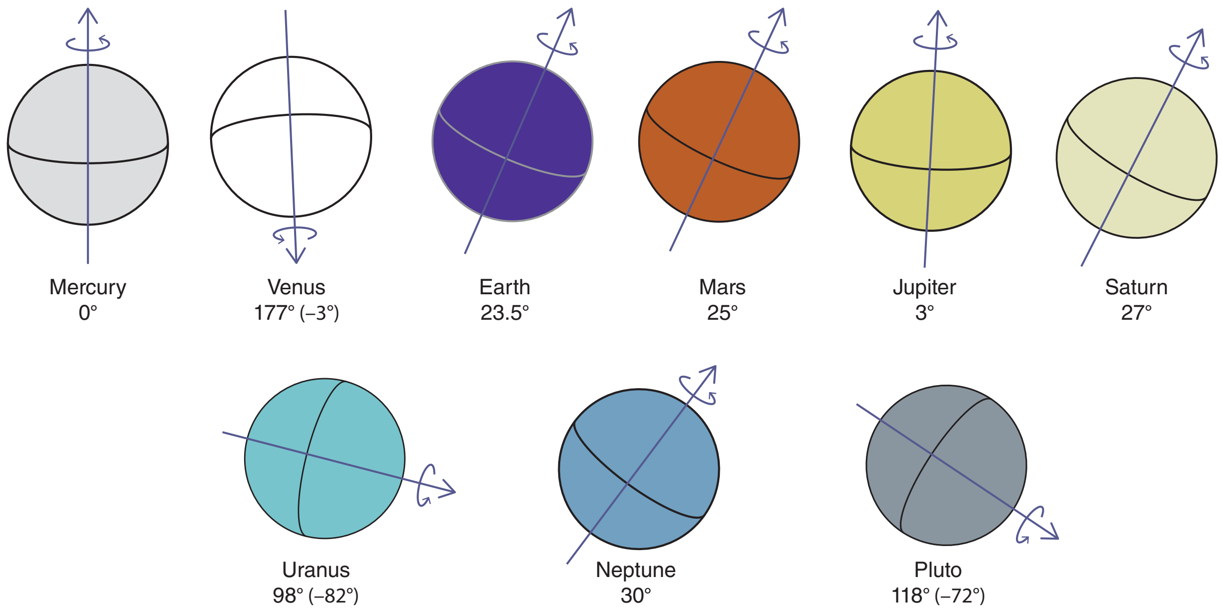


Figure 1.12 The axial inclinations (obliquities) of the planets and Pluto compared to their orbital planes. Most of the planets have axial tilts of less than 90°, so they rotate in a prograde direction, from west to east. Venus, Uranus, and Pluto have obliquities greater than 90°, so they are said to rotate in a retrograde (backwards) direction. (Peter Bond)

at a greater distance from the protostar, where gas pressure was lower.

Such a nebula would almost certainly rotate slowly in the early stages, but as it contracts, conservation of angular momentum causes the cloud to spin faster. If this process continues, the core forming at the center of the nebula will spin up so fast that it flies apart before it has a chance to form a star. Somehow, that angular momentum must be removed before a star can form.

Studies of other young stars and their surrounding disks provide evidence that, as the interstellar gas collapses, it also winds up the magnetic field which permeates the nebula. Gas which is rotating too fast to collapse is expelled and dispersed along the magnetic field.

This process naturally forms a spiral-shaped magnetic field that helps to generate polar jets and outflows associated with very young stars. At the same time, the jets remove angular momentum, allowing other material to accrete and collapse. Gravitational instability, turbulence, and tidal forces within the "lumpy" disk may also play a part, helping to transfer much of the angular momentum to the outer regions of the forming disk.

The protoplanetary disk is heated by the infall of material. The inner regions, where the cloud is most massive, become hot enough to vaporize dust and ionize gas. As contraction continues and the cloud becomes increasingly dense, the temperature at its core reaches the point where nuclear fusion commences. The emerging protostar begins to emit copious amounts of ultraviolet radiation. Radiation pressure drives away much of the nearby dust, causing the star to decouple from its nebula.

The young star may remain in this T Tauri stage for perhaps 10 million years, after which most of the residual nebula has evaporated or been driven into interstellar space. All that remains of the original cloud is a rarefied disk of dust grains, mainly silicates and ice crystals.

Meanwhile, the seeds of the planets have begun to appear. More refractory elements condense in the warm, inner regions of the nebula, while icy grains condense in the cold outer regions. Individual grains collide and stick together, growing into centimeter-sized particles. These swirl around at different rates within the flared disk, partly due to turbulence and partly as the result of differences in the drag exerted by the gas. After a few million years, these dusty or icy golf balls accrete into kilometer-sized planetesimals and gravity becomes the dominant force.

The Solar System now resembles a shooting gallery, with objects moving at high speed in chaotic fashion and enduring frequent collisions with each other. Some of these impacts are destructive, causing the objects to shatter and generate large amounts of dust or meteorite debris. Other collisions are constructive, resulting in a snowballing process. Over time, the energy loss resulting from collisions means that construction eventually dominates.

Eventually, the system contains a relatively small number of large bodies or protoplanets. Millions of years pass as they continue to mop up material from the remnants of the solar nebula and to collide with each other, finally resulting in a population of widely separated worlds occupying stable orbits and traveling in the same direction around the young central star.

It is likely that the largest planets in the Solar System, Jupiter and Saturn, formed first. They presumably accumulated their huge gaseous envelopes of hydrogen and helium before the solar nebula dispersed.

Box 1.2 Kepler's Laws of Planetary Motion

Johannes Kepler (1571–1630) was one of the most important characters in the story of unraveling how the Solar System works. The German-born mathematician was appointed assistant to Tycho Brahe (1546–1601), the most famous observer of the day. Granted access to Brahe's catalog of positional data, Kepler was given the task of explaining the orbit of Mars. After four years of calculations, Kepler finally realized in 1605 that the orbits of the planets were not perfect circles, but elongated circles known as ellipses.

Whereas a circle has one central point, an ellipse has two key interior points called foci (singular: focus). **The sum of the distances from the foci to any point on the ellipse is a constant**. For Solar System objects, the Sun always lies at one focus.

In order to draw an ellipse, place two drawing pins some distance apart and loop a piece of string around them. Place a pencil inside the string, draw the string tight and move the pencil around the pins. Now move one of the pins and repeat the process. Note how the shape of the ellipse has changed.

The amount of "stretching" or "flattening" of the ellipse is termed its eccentricity. All ellipses have eccentricities lying between zero and one. A circle may be regarded as an ellipse with zero eccentricity. As the ellipse becomes more stretched, its eccentricity approaches one.

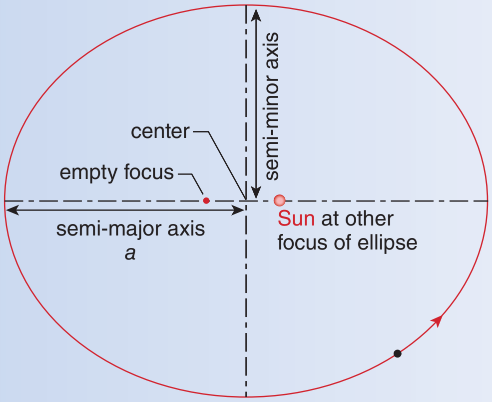


Figure 1.13 A circle has an eccentricity of zero. As the ellipse becomes more stretched (i.e. the foci move further apart) the eccentricity approaches one. Half of the major axis is termed the semi-major axis. The average distance of a planet from the Sun as it follows its elliptical orbit is equal to the length of the semi-major axis. The eccentricity is calculated by dividing the distance between the two foci by the length of the major axis. (Peter Bond)

In reality, most of the planets follow orbits that are only slightly elliptical. Their eccentricities are so small that they look circular at first glance. Pluto and Mercury are the main exceptions, with eccentricities exceeding 0.2.

Another key characteristic of an ellipse is its maximum width, known as the major axis. Half of the major axis is termed the semi-major axis. The average distance of a planet from the Sun as it goes around its elliptical orbit is equal to the length of the semi-major axis.

After intensive work on the implications of his discovery, Kepler eventually formulated his *Three Laws of Planetary Motion*.

- **Kepler's First Law: The orbits of the planets are ellipses, with the Sun at one focus of the ellipse.** (Generally, there is nothing at the other focus.)
- **Kepler's Second Law: The line joining the planet to the Sun sweeps out equal areas in equal times as the planet travels around the ellipse**. In order to do so, a planet must move faster along its orbit near the Sun and more slowly when it is far away. A planet's point of nearest approach to the Sun is termed perihelion; the furthest point from the Sun on its orbit is termed aphelion. Hence, a planet moves fastest when it is near perihelion and slowest when it is near aphelion.
- **Kepler's Third Law: The square of a planet's sidereal (orbital) period is proportional to the cube of its mean distance (semi-major axis) from the Sun**. This means that the period, or length of time a planet takes to complete one orbit around the Sun, increases rapidly with its distance from the Sun. Thus, Mercury, the innermost planet, takes only 88 days to orbit the Sun, whereas remote Pluto takes 248 years to do the same.

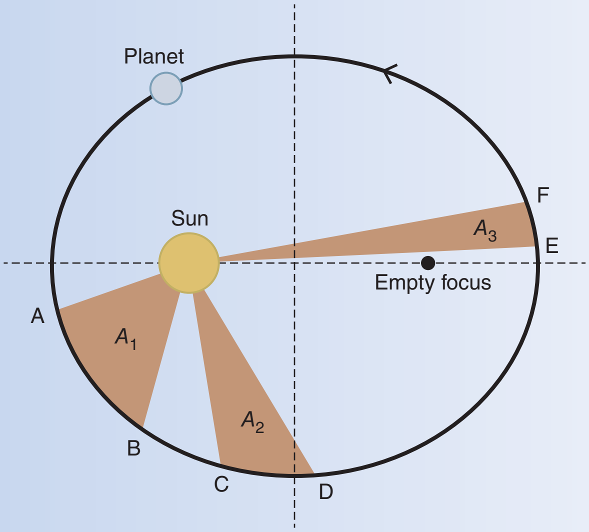


Figure 1.14 Kepler's first law states that the orbit of a planet about the Sun is an ellipse with the Sun at one focus. The other focus of the ellipse is empty. According to Kepler's second law, the line joining a planet to the Sun sweeps out equal areas in equal times. In this diagram, the three shaded sectors, A_1, A_2, and A_3, all have equal areas. A planet takes as long to travel from A to B as from C to D and E to F, because it moves most rapidly when it is nearest the Sun (at perihelion) and slowest when it is farthest from the Sun (at aphelion). (Peter Bond)

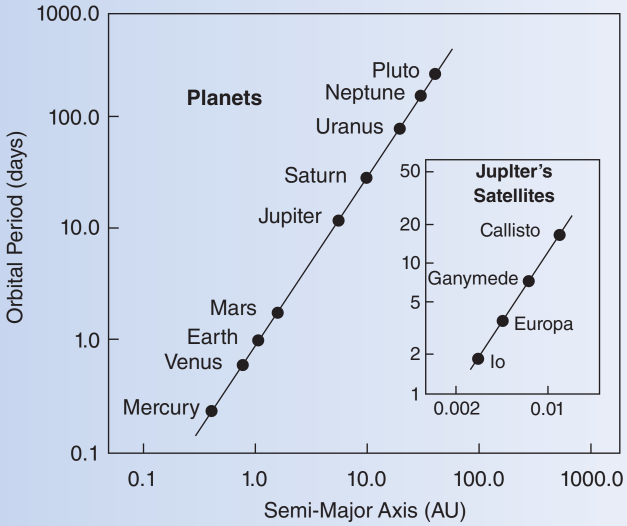


Figure 1.15 A graph showing the orbital periods of the planets plotted against their semi-major axes, using a logarithmic scale. The straight line that connects the planets has a slope of 3/2, verifying Kepler's third law which states that the squares of the orbital periods increase with the cubes of the planetary distances. This law applies to any bodies in elliptical orbits, including Jupiter's four largest satellites (inset). (Kenneth R. Lang, The Cambridge Guide to the Solar System)

This law can be used to make some useful, but fairly simple, calculations. For example, if the period is measured in Earth years and the distance is measured in astronomical units (AU), the law may be written in the simple form: $P(\text{years})^2 = R(\text{AU})^3$.

This equation may also be written as: $P(\text{years}) = R(\text{AU})^{3/2}$. Thus, if we know that Pluto's average distance from the Sun (semi-major axis) is 39.44 AU, we can calculate that its orbital period $P = (39.44)^{3/2} = 247.69$ years. Similarly, if we know that Mars takes 1.88 Earth years to orbit the Sun, we can calculate that its semi-major axis $R = (1.88)^{2/3} = 1.52$ AU.

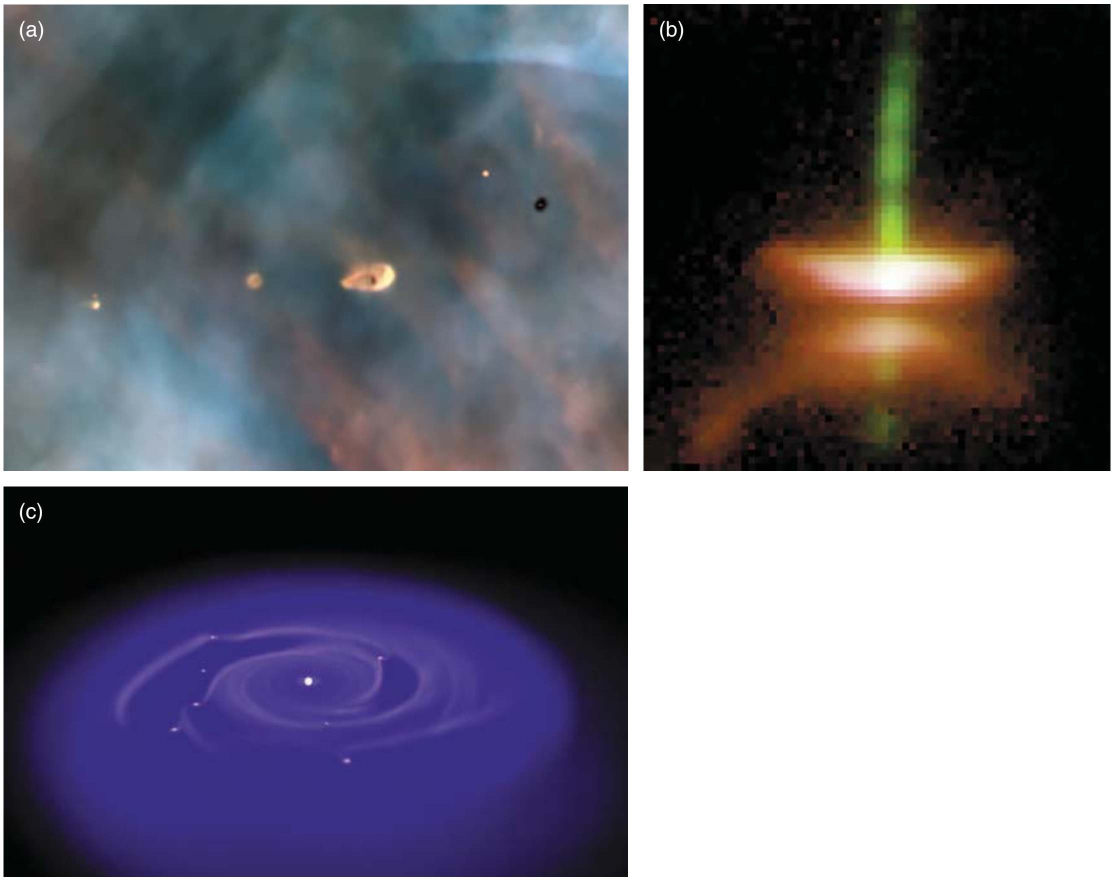


Figure 1.16 The early stages of star and planet formation. (a) A Hubble Space Telescope view of five young stars in the Orion Nebula. Four are surrounded by gas and dust trapped in orbit as the stars formed. These are possibly protoplanetary disks, or "proplyds," that might eventually produce planets. The bright proplyds are closest to the hottest stars of the parent star cluster, while the object farthest from the hottest stars appears dark. (C. R. O'Dell/Rice University; NASA) (b) This HST image shows Herbig-Haro 30, a young star surrounded by a thin, dark disk. The disk extends 64 billion km, dividing the nebula in two. The central star is hidden from direct view, but its light reflects off the upper and lower surfaces of the disk to produce the pair of reddish nebulas. Gaseous jets (green) remove material from above and below the disk and transfer angular momentum outwards. (Chris Burrows/STScI, the WFPC2 Science Team and NASA) (c) A computer simulation showing how a protoplanetary disk surrounding a young star begins to fragment and form gas giant planets with stable orbits. (Mayer, Quinn, Wadsley, Stadel, 2002, Science)

Observations of young star systems show that the gas disks that form planets usually have lifetimes of only 1 to 10 million years, which means the gas giant planets probably formed within this time frame. In contrast, Earth probably took at least 30 million years to form, and may have taken as long as 100 million years.

It is worth noting here that computer simulations of the early Solar System show that even the slightest differences in initial conditions can produce different planetary systems. Depending on exactly where each embryo started out, the orbital positions of new planets vary randomly from simulation to simulation. The total number of planets – and hence, their final masses – may also vary greatly. It seems that planet formation is a very chaotic process as evidenced by exoplanet systems which bear little resemblance to our Solar System (see Chapter 14).

Rocky Planets

Modeling suggests that collisions between planetesimals initially occur at low velocities, allowing them to merge and grow (Box 1.3). At the Earth's distance from the Sun, it takes only about 1,000 years for 1-km-sized objects to grow into 100-km objects. Another 10,000 years produces 1,000-km diameter protoplanets, which double in diameter over the next 10,000 years. Such models indicate that Moon-sized objects can form in a little over 20,000 years.

As planetesimals within the protosolar disk grow larger and more massive, their gravity increases, and once a few of the objects reach a size of 1,000 km, they begin to stir up the remaining smaller objects. Near encounters accelerate the smaller, asteroid-sized chunks of rock to higher and higher speeds.

Box 1.3 Key Steps in the Formation of Rocky Planets (after Kenyon and Bromley)

1. A molecular cloud made up of gas and dust begins to collapse.
2. A protostar begins to form at the core of the collapsing nebula.
3. A disk-shaped nebula of orbiting dust and gas develops in the protostar's equatorial plane.
4. Dust grains in the disk collide and merge.
5. Large (1 mm) dust grains fall into a thin, dusty sheet.
6. Collisions produce planetesimals 1 m to 1 km across.
7. More collisions between planetesimals produce planetary embryos.
8. Planetary embryos stir up the leftover planetesimals.
9. Planetesimals then collide and fragment.
10. A cascade of collisions reduces fragments to dust.
11. Planets sweep up some of the dust.
12. Radiation and a "wind" of charged particles from the central star remove the remaining gas and dust.

Eventually, they are traveling so quickly that when they collide, they pulverize each other instead of merging.

While the largest protoplanets continue to grow, the remaining rocky planetesimals grind each other into dust. Some of this dust is drawn in by the surviving planets, while much of the remainder is swept out of the Solar System when the Sun evolves into a hydrogen-burning star. (A cloud of micron-sized dust particles still exists in the ecliptic plane of the Solar System. Known as the zodiacal cloud, it is composed of silicate particles that are largely derived from collisions between main belt asteroids.)

One of the problems that must be solved by Solar System theorists is an explanation for the silicate and metal-rich nature of the terrestrial planets and the dominance of hydrogen and helium in the outer planets (Box 1.4). Clearly, the marked difference in composition between the inner and outer planets must be related to the materials that made up different regions of the disk.

The dense, rocky nature of the Earth and its neighbors suggests that they simply formed through the accretion of dust grains in the solar nebula. However, studies of primitive chondritic meteorites show the presence of millimeter-sized droplets (chondrules) that were once liquid.

It seems that, before they amalgamated to form the meteorites, these existed for a brief period as independent spheroids at temperatures above 1,500°C. Some chondrules seem to include other chondrules, indicative of being exposed to high temperatures on more than one occasion (see Chapter 13). The source of the heating is uncertain, although shock waves, solar heating, and collisions between planetesimals have been suggested.

Laboratory experiments indicate that these molten globules were cooled very rapidly, within 10 million years of the collapse of the molecular cloud. The cause of such sudden cooling events remains unclear. What does seem certain is that the chondrules and dust began to stick together and grow in size, creating chunks of chondritic material. Drag from gas in the nebula encouraged the pebble-sized objects to creep inward, all the time gathering in more material.

Once a population of large planetesimals evolved, their destiny was determined largely by chance. A fast, head-on collision caused the objects to break apart. A slow, gentler encounter enabled the participants to merge into an even larger object. In this way, the terrestrial planets grew to more or less their current size over a period of some 10 million years.

The huge amounts of kinetic energy dumped in the planets by frequent, massive impacts caused partial or total melting and the creation of magma oceans. This led to internal differentiation, with the denser elements, such as iron, sinking to the core and the lighter ones rising to the surface to create silicate crusts.

Early atmospheres were generated by outgassing of volatile molecules such as water, methane, ammonia, hydrogen, nitrogen, and carbon dioxide. A final heavy bombardment, which ended about 3.8 billion years ago, is clearly marked in the crater record of the Moon, and this has been applied to other planets and satellites.

Occasionally a satellite was created as the by-product of a major impact. Such is thought to be the case with Earth and its Moon. Debris from an ancient collision between the young Earth and a Mars-sized planetesimal created a ring of debris that eventually came together to form the Moon. A similar explanation has been put forward for the satellites of Mars and the Pluto-Charon system (see Chapters 7 and 12).

Gas Giants and Ice Giants

In the outer reaches of the solar nebula, temperatures were low enough for ices to form. Indeed, it seems that ice particles were much more abundant than silicate dust particles. This being the case, any planetesimals born in the frigid outer zone would have resembled icy dirt balls, much like the comets we see today. However, the main constituents of Jupiter and Saturn are hydrogen and helium, rather than water. Since temperatures in the nebula would have been too warm for these gases to condense, accretion of hydrogen and helium snowflakes cannot have occurred. Another explanation must be found.

There seem to be two possibilities. Studies of gas giant interiors suggest that Jupiter and Saturn may possess rocky cores at least as large as the Earth. It may be, therefore, that the early stages of growth of these planets resembled the accretion taking place in the inner Solar System, with the growth of massive nuclei of ice and dust. Once these became sufficiently large, about five to 15 times the mass of Earth, they were able to attract and hold onto even the lightest gases in the surrounding solar nebula. As their mass and gravitational grasp grew, their spheres became ever more bloated.

Alternatively, they could simply have developed as the result of large-scale gravitational instabilities in the solar nebula. Since