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Kenneth R. Lang
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The Cambridge Guide to the Solar System

Richly illustrated with full-color images, this book is a comprehensive, up-to-date description of the planets, their moons, and recent exoplanet discoveries.

The second edition of this classic reference is brought up-to-date with the fascinating new discoveries made during recent years from 12 new solar system missions. Representative examples include water on the Moon; widespread volcanism on Mercury's previously unseen half; vast buried glaciers on Mars; geysers on Saturn's active water moon Enceladus; lakes of methane and ethane on Saturn's moon Titan; the encounter with asteroid Itokawa; and an encounter and sample return from comet Wild 2. The book is further enhanced by hundreds of striking new images of the planets and moons.

Written at an introductory level appropriate for high-school and undergraduate students, it provides fresh insights that appeal to anyone with an interest in planetary science. A website hosted by the author contains all of the images in the book with an overview of their importance. A link to this can be found at www.cambridge.org/solarsystem/.

KENNETH R. LANG is a Professor of Astronomy at Tufts University. He is a well-known author and has published 25 books. *The Cambridge Encyclopedia of the Sun* (Cambridge University Press, 2001) was recommended by the *Library Journal* as one of the best reference books published that year. He has extensive teaching experience, and has served as a Visiting Senior Scientist at NASA Headquarters.

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Several Circles. January–February 1926. The artist Vasily Kandinsky (1866–1944) seems to capture the essence of our space-age exploration of previously unseen worlds in this cosmic and harmonious painting. According to Kandinsky, "The circle is the synthesis of the greatest oppositions. It combines the concentric and the eccentric in a single form and in equilibrium. Of the three primary forms, it points most clearly to the fourth dimension." (Courtesy of the Solomon R. Guggenheim Museum, New York City, New York.)

The Cambridge Guide to the Solar System

Second Edition

Kenneth R. Lang
Tufts University, Medford, Massachusetts, USA

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Preface to the second edition

The second edition of *The Cambridge Guide to the Solar System* brings this comprehensive description of the planets and moons up to date, by extending it to include fascinating new discoveries made during the previous decade. As with the first edition, it is written at an introductory level appropriate for high-school and undergraduate students, while also providing fresh, current insights that will appeal to professionals as well as general readers with an interest in planetary science. This is accomplished in a light and uniform style, including everyday metaphors and many spacecraft images.

This second edition is filled with vital new facts and information, and lavishly illustrated in color throughout. Hundreds of new images have been provided. Most of these illustrations have never appeared together in print before, and many of them have a beauty comparable to works of art.

An Internet site for use by the instructor, students or casual reader also supports this book. It contains all of the images in this second edition, together with their legends and overview bullets of their seminal content. This site also includes similar material for the author's books about the Sun, including the second edition of *Sun, Earth and Sky* and the second edition of *The Sun from Space*. The website address is http://ase.tufts.edu/cosmos/.

Striking examples of new images from contemporary planetary spacecraft include the *Chandrayaan-1* and *LCROSS* missions to the Moon, the *MESSENGER* spacecraft that is viewing the unseen half of Mercury, the *2001 Mars Odyssey*, *Spirit* and *Opportunity Exploration Rovers* and *Phoenix* lander on Mars, the *Cassini–Huygens* mission to Saturn and its moons Enceladus and Titan, the *Deep Impact* and *Stardust* encounters with comets, with *Stardust*'s sample return to Earth, and the *Hayabusa* encounter with the asteroid Itokawa.

The more effective illustrations from previous spacecraft have been retained, without an excessive increase in the length of the book, including those from the *Apollo* missions to the Earth's Moon, the *Viking 1* and *2* missions to Mars, the *Mars Global Surveyor*, the *Voyager 1* and *2* missions to the four giant planets, the *Galileo* mission to Jupiter, and several spacecraft encounters with asteroids and comets.

We have not forgotten our home planet Earth, which continues to provide the reference background for discussions of volcanoes, water, geology, atmospheres and magnetospheres. The second edition also includes an updated appraisal of the effects of global warming, with attempts to combat it, and investigations of space weather that can threaten astronauts and influences the performance, reliability and lifetime of interplanetary spacecraft, Earth-orbiting satellites, and terrestrial communications and power systems.

A new chapter, entitled 'Beyond Neptune', takes us to the outer precincts of the planetary realm, with the discovery of several worlds that orbit the Sun beyond the orbit of Neptune. At least three of these dwarf planets are either larger than Pluto or comparable to it in size, and along with Pluto they have also been designated Plutoids. Three companion moons are also now known to orbit Pluto, and its tenuous atmosphere and surface markings have been scrutinized in anticipation of the encounter of the *New Horizons* spacecraft with Pluto in 2015. In the meantime, the *Voyager 1* and *2* spacecraft have traveled far beyond the planets and measured the termination shock of the Sun's winds at about 100 times the distance between the Earth and the Sun.

An entirely new end-chapter describes the origin of our solar system and the exciting new discoveries of hundreds of planets orbiting nearby stars other than the Sun. These extrasolar planets, or exoplanets for short, include multiplanet systems and are mainly hot Jupiters, which revolve unexpectedly close to their star and have masses comparable to that of Jupiter. But atmospheres have been found on some of these new exoplanets, and astronomers are also finding super-Earths of just a few times the mass of the Earth. Astronomers are now finding Earth-size planets that reside in the warm habitable zone where liquid water can exist on the planet's surface and living things might be present.

The main body of this second edition does not simply consist of a few updates or cosmetic patch ups of the material in the first edition. It instead contains all of the relevant new discoveries, ideas and information resulting from recent planetary spacecraft. They include: water on the Moon; evidence for widespread volcanic activity on young Mercury; ubiquitous evidence for ancient water flows and vast amounts of frozen water now on Mars; jets of ice particles, water vapor and organic compounds from Saturn's active water moon Enceladus; organic dunes and rain and lakes of liquid methane and ethane on Saturn's moon Titan; close-up details of Saturn's rings and its enigmatic moons Hyperion and Phoebe, immersed within a newly discovered ring; asteroid Itokawa's loose collection of rubble; the return of comet dust, containing organic molecules, from comet Wild 2 to Earth; and the *Deep Impact* collision with comet Tempel 1, with forced ejections of water vapor, water ice and other substances.

In addition to bringing images and discoveries up to date, the second edition also adds more scientific substance with set-aside *focus boxes* that emphasize basic planetary physics at the algebra level, such as the luminosity and temperature of the Sun; conservation of angular momentum in the Earth–Moon system; escape velocity, temperature and retention of planetary atmospheres; the Roche limit, and gravitational collapse. These interesting boxed set-asides can be used in introductory university courses that include fundamental scientific topics, but they are not a crucial aspect of the main text and can be bypassed by students with non-scientific interests or by the general reader.

In short, this is a fine, stimulating collection of exciting spacecraft images and marvelous discoveries about the planets and moons, as well as exoplanets, and I hope the reader derives as much pleasure as I have from finding out about them.

I am grateful to three bright, alert Tufts students, Laura Costello, Jeffrey Gottlieb and Nathaniel Eckman, for reading draft chapters of this book, offering insightful comments and spotting necessary corrections. This volume was also substantially improved by the careful editing of Sue Glover. Special thanks are extended to Joe Bredekamp at NASA Headquarters who has actively encouraged the writing of this book and helped fund it through NASA Grant NNX07AU93G with NASA's Applied Information Systems Research Program.

Kenneth R. Lang
Tufts University

Preface to the first edition

The planets have been the subject of careful observations and myth for millennia and the subject of telescopic studies for centuries. Our remote ancestors looked into the night sky, and wondered why the celestial wanderers or planets moved across the stellar background. They saw the planets as powerful gods, whose Greek and Roman names are still in use today. Then progressively larger telescopes enabled the detection of faint moons and remote planets that cannot be discerned with the unaided eye, and resolved fine details that otherwise remain blurred.

Only in the past half century have we been able to send spacecraft to the planets and their moons, changing many of them from moving points of light to fascinating real worlds that are stranger and more diverse than we could have imagined. Humans have visited the Moon, and robot spacecraft have landed on Venus and Mars. We have sent vehicles to the very edge of the planetary system, capturing previously unseen details of the remote giant planets, dropping a probe into Jupiter's stormy atmosphere, and perceiving the distant satellites as unique objects whose complex and richly disparate surfaces rival those of the planets. Probes have also been sent to peer into the icy heart of two comets, and robotic eyes have scrutinized the battered and broken asteroids.

The Cambridge Guide to the Solar System is a complete modern guide, updating and extending the prize-winning *Wanderers in Space* – Prix du livre de l'Astronomie in 1994. This book, written by the author and Charles A. Whitney, was completed before the *Clementine* and *Lunar Prospector* spacecraft were sent to the Moon, the *Magellan* orbiter penetrated the veil of clouds on Venus, the *Mars Pathfinder* landed on the red planet with its mobile roving *Sojourner*, the *Mars Global Surveyor* obtained high-resolution images of the surface of Mars, the *NEAR-Shoemaker* spacecraft orbited the asteroid 433 Eros, the *Galileo* orbiter and probe visited Jupiter and its four large moons, *Deep Space 1* peered into the nucleus of Comet Borrelly, and Comet Shoemaker–Levy 9 collided with Jupiter. *The Guide* updates *Wanderers* to include the captivating results of all these missions, presenting more than a half century of extraordinary accomplishment.

The Cambridge Guide to the Solar System provides comprehensive accounts of the most recent discoveries, from basic material to detailed concepts. It is written in a concise, light and uniform style, without being unnecessarily weighed down with incomprehensible specialized materials or the variable writing of multiple authors. Metaphors, similes and analogies will be of immense help to the lay person and they add to the enjoyment of the material. Vignettes containing historical, literary and even artistic material make this book unusual and interesting, but at a modest level that enhances the scientific content of the book and does not interfere with it.

The book is at once an introductory text of stature and a thorough, serious and readable report for general readers, with much compact reference data. The language, style, ideas and profuse illustrations will attract the general reader as well as students and professionals. In addition, it is filled with vital facts and information for astronomers of all types and for anyone with a scientific interest in the planets and their satellites.

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The many full-color images, photographs, and line drawings help make this information highly accessible.

Each chapter begins with a set of pithy, one-sentence statements that describe the most important or interesting things that will be described in that chapter. A summary diagram, placed at the end of each chapter, captures the essence of our knowledge of the subject.

Set-aside *focus boxes* enhance and amplify the discussion with interesting details, fundamental physics and important related topics. They will be read by the especially curious person or serious student, but do not interfere with the general flow of the text and can be bypassed by the general educated reader who wants to follow the main ideas. Equations are kept to a minimum and, when employed, are almost always placed within the set-aside *focus elements*.

Numerous tables provide fundamental physical data for the planets and large moons. Many graphs and line drawings complement the text by summarizing what spacecraft have found. Guides to other resources are appended to the book as an annotated list of books for further reading, all published after 1990, and a list of relevant Internet addresses.

The Cambridge Guide to the Solar System has been organized into four main parts. The first introduces the planets and their moons, with a brief historical perspective followed by a discussion of their common properties. These unifying features include craters, volcanoes, water, atmospheres and magnetic fields. The second part discusses the rocky worlds found in the inner solar system – the Earth with its Moon, Mercury, Venus and Mars. The third part presents the giant planets, their satellites and their rings – worlds of liquid, ice and gas. The last part discusses the smaller worlds, the comets and asteroids, as well as collisions of these bodies with Jupiter, the Sun and Earth.

Chapter 1 traces our evolving understanding of the planets and their satellites made possible by the construction of ever-bigger telescopes. They resulted in the discovery of new planets and satellites, and resolved details on many of them. Here we include, in chronological order, the discoveries of Jupiter's moons, Saturn's rings, Uranus, Neptune, the asteroids, the icy satellites of the giant planets, tiny Pluto with its oversized moon, and the small icy objects in the Kuiper belt at the edge of the planetary realm. Other fundamental discoveries have been woven into the fabric of this chapter, including the realization that planets are whirling endlessly about the Sun, refinements of the scale and size of the planetary realm, and the spectroscopic discovery of the main ingredients of both the Sun and the atmospheres of the planets.

Chapter 2 begins with a description of how spacecraft have fundamentally altered our perception of the solar system, providing detailed close-up images of previously unseen landscapes and detecting incredible new worlds with sensors that see beyond the range of human vision. These new vistas have also resulted in a growing awareness of the similarities of the major planets and some moons. In the rest of Chapter 2 and in Chapter 3, they are therefore interpreted as a whole, rather than as isolated objects, by presenting comparative aspects of common properties and similar processes. This provides a foundation for subsequent examination of individual objects in greater detail.

Impact craters are found on just about every body in the solar system from the Moon and Mercury to the icy satellites of the distant planets, but in different amounts that depend on their surface ages and with varying properties. Ancient impacts on Venus have, for example, been erased by outpourings of lava, and the debris from subsequent impacts has been shaped by the planet's thick atmosphere. Numerous volcanoes have also been found throughout the solar system, including fiery outbursts on the Earth, towering volcanic mountains on Mars, numerous volcanoes that have resurfaced Venus, currently active volcanoes that have turned Jupiter's satellite Io inside out, and eruptions of ice on Neptune's largest moon, Triton.

Liquid water, which is an essential ingredient of life, covers seventy-one percent of the Earth's surface. Catastrophic floods and deep rivers once carved deep channels on Mars, and spring-like flows have been detected in relatively recent times. Water ice is ubiquitous in the outer solar system, including the clouds of Jupiter, the rings of Saturn, and the surfaces of most satellites. There is even evidence for subsurface seas beneath the water-ice crusts of Jupiter's satellites Europa, Ganymede and Callisto, and liquid water might also reside beneath the frozen surface of Saturn's satellite Enceladus.

Chapter 3 describes the atmospheres and magnetic fields that form an invisible buffer zone between planetary surfaces and surrounding space. Venus has an atmosphere that has run out of control, smothering this nearly Earth-sized world under a thick blanket of carbon dioxide. Its greenhouse effect has turned Venus into a torrid world that is hot enough to melt lead and vaporize oceans. Mars now has an exceedingly thin, dry and cold atmosphere of carbon dioxide. The red planet breathes about one-third of its atmosphere in and out as the southern polar cap grows and shrinks with the seasons. Jupiter's powerful winds and violent storms have remained unchanged for centuries, and Neptune has an unexpectedly stormy atmosphere. Saturn's largest moon, Titan, has a substantial Earth-like atmosphere, which is mainly composed of nitrogen and has a surface pressure comparable to that of the Earth's atmosphere. Temporary, rarefied and misty atmospheres cloak the Moon, Mercury, Pluto, Triton, and Jupiter's four largest moons.

Magnetic fields protect most of the planets from energetic charged particles flowing in the Sun's ceaseless winds, but some electrons and protons manage to penetrate this barrier. Jupiter's magnetism is the strongest and largest of all the planets, as befits the giant, while the magnetic fields of Uranus and Neptune are tilted. Guided by magnetic fields, energetic electrons move down into the polar atmospheres of Earth, Jupiter and Saturn, producing colorful auroras there.

Our description of individual planets begins in Chapter 4, with our home planet Earth. Earthquakes have been used to look inside our world, determining its internal structure and locating a spinning, crystalline globe of solid iron at its center. At the surface, continents slide over the globe, colliding and coalescing with each other like floating islands, as ocean floors well up from inside the Earth.

A thin membrane of air protects life on this restless world, and that air is being dangerously modified by life itself. Synthetic chemicals have been destroying the thin layer of ozone that protects human beings from dangerous solar ultraviolet radiation, and wastes from industry and automobiles are warming the globe to dangerous levels. The world has become hotter in the last decade than it has been for a thousand years, and at least some of this recent rise in temperature is due to greater emissions of greenhouse gases by human activity. The politicized debate over global warming is also described in Chapter 4, as are the probable future consequences if we don't do something about it soon.

This fourth chapter also discusses how the Sun affects our planet, where solar light and heat permit life to flourish. The amount of the Sun's radiation that reaches the Earth varies over the 11-year solar cycle of magnetic activity, warming and cooling the planet. Further back in time, during the past one million years, our climate has been changed by the recurrent ice ages, which are caused by variations in the amount and distribution of sunlight reaching the Earth.

An eternal solar gale now buffets our magnetic domain and sometimes penetrates it. Forceful mass ejections can create powerful magnetic storms on Earth, and damage or destroy Earth-orbiting satellites. Energetic charged particles, hurled out during solar explosions, endanger astronauts and can also wipe out satellites that are so important to our technological society. Space-weather forecasters are now actively searching for methods to predict these threats from the Sun.

In Chapter 5 we continue on to the still, silent and lifeless Moon, a stepping stone to the planets. Most of the features that we now see on the Moon have been there for more than 3 billion years. Cosmic collisions have battered the lunar surface during the satellite's formative years, saturating much of its surface with impact craters, while lunar volcanism filled the largest basins to create the dark maria.

Twelve humans went to the Moon more than three decades ago, and brought back nearly half a ton of rocks. The rocks contain no water, have never been exposed to it, and show no signs of life. Yet, orbiting spacecraft have found evidence for water ice deposited by comets in permanently shaded regions at the lunar poles.

The fifth chapter also describes how the Moon generates tides in the Earth's oceans, and acts as a brake on the Earth's rotation, causing the length of day to steadily increase. The satellite also steadies our seasons by limiting the tilt of Earth's rotation axis. The story of the Moon's origin is given the latest and most plausible explanation: a glancing impact from a Mars-sized object knocked a ring of matter out of the young Earth; that ring soon condensed into our outsized, low-density Moon.

We discover in Chapter 6 that Mercury has an unchanging, cratered and cliff-torn surface like the Moon, but in a brighter glare from the nearby Sun. Although the planet looks like the Moon on the outside, it resembles the Earth on the inside. Relative to its size, Mercury has the biggest iron core of all terrestrial planets, and it also has a relatively strong magnetic field. Here we also mention tiny, unexplained motions of Mercury. As demonstrated by astronomers long ago, the planet does not appear precisely in its expected place. This discrepancy led Einstein to develop a new theory of gravity in which the Sun curves nearby space.

Chapter 7 discusses veiled Venus, the brightest planet in the sky. No human eye has ever gazed at its surface, which is forever hidden in a thick overcast of impenetrable clouds made of droplets of concentrated sulfuric acid. Radar beams from the orbiting *Magellan* spacecraft have penetrated the clouds and mapped out the surface of Venus in unprecedented detail, revealing rugged highlands, smoothed-out plains, volcanoes and sparse, pristine impact craters. Rivers of outpouring lava have resurfaced the entire surface of Venus, perhaps about 750 million years ago, and tens of thousands of volcanoes are now found on its surface. Venus exhibits every type of volcanic edifice known on Earth, and some that have never been seen before. Some of them could now be active. Unlike Earth, there is no evidence for colliding continents on Venus, its surface moves mostly up and down, rather than sideways. Vertical motions associated with upwelling hot spots have buckled, crumpled, deformed, fractured and stretched the surface of Venus.

Our voyage of discovery continues in Chapter 8 to the red planet Mars, long thought to be a possible haven for life. Catastrophic flash floods and deep ancient rivers once carved channels on its surface, and liquid water might have lapped the shores of long-vanished lakes and seas. But its water is now frozen into the ground and ice caps, and it cannot now rain on Mars. Its thin, cold atmosphere lacks an ozone layer that might have protected the surface from lethal ultraviolet rays from the Sun, and if any liquid water were now released on the red planet's surface it would soon evaporate or freeze. Yet underground liquid water may have been seeping out of the walls of canyons and craters on Mars in recent times.

Three spacecraft have landed on the surface of Mars, failing to detect any unambiguous evidence for life. Corrosive chemicals have destroyed all organic molecules in the Martian ground, which means that the surface now contains no cells, living, dormant or dead. A meteorite from Mars, named ALH 84001, exhibits signs that bacteria-like micro-organisms could have existed on the red planet billions of years ago, but most scientists now think that there is nothing in the meteorite that conclusively indicates whether life once existed on Mars or exists there now. The future search for life on Mars may include evidence of

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microbes that can survive in hostile environments, perhaps energized from the planet's hot interior.

Chapter 9 presents giant Jupiter, which is almost a star and radiates its own heat. Jupiter radiates nearly twice as much energy as it receives from the Sun, probably as heat left over from when the giant planet formed. Everything we see on Jupiter is a cloud, formed in the frigid outer layers of its atmosphere. The clouds are swept into parallel bands by the planet's rapid rotation and counter-flowing winds, with whirling storms that can exceed the Earth in size. The fierce winds run deep and are driven mainly from within by the planet's internal heat. The biggest storms and wind-blown bands have persisted for centuries, though the smaller eddies are engulfed by the bigger ones, deriving energy from them. The little storms pull their energy from hotter, lower depths. Jupiter has a non-spherical shape with a perceptible bulge around its equatorial middle, and this helps us determine what is inside the planet. It is almost entirely a vast global sea of liquid hydrogen, compressed into a fluid metal at great depths. And above it all, Jupiter has a faint, insubstantial ring system that is made of dust kicked off small nearby moons by interplanetary meteorites.

Chapter 9 additionally provides up-to-date accounts of the four large moons of Jupiter, known as the Galilean satellites. The incredible complexity and rich diversity of their surfaces, which rival those of the terrestrial planets, are only visible by close-up scrutiny from spacecraft. Although the *Voyager 1* and *2* spacecraft sped by with just a quick glimpse at them, it was time enough for their cameras to discover new worlds as fascinating as the planets themselves, including active volcanoes on Io, smooth ice plains on Europa, grooved terrain on Ganymede, and the crater-pocked surface of Callisto. Then the *Galileo* spacecraft returned for a longer look, gathering further data on the satellites' surfaces and using gravity and magnetic measurements to infer their internal constitution. Changing tidal forces from nearby massive Jupiter squeeze Io's rocky interior in and out, making it molten inside and producing the most volcanically active body in the solar system. Jupiter's magnetic field sweeps past the moon, picking up a ton of sulfur and oxygen ions every second and directing them into a doughnut-shaped torus around the planet. A vast current of 5 million amperes flows between the satellite Io and the poles of Jupiter and back again, producing auroral lights on both bodies. There are no mountains or valleys on the bright, smooth, ice-covered surface of Europa. The upwelling of dirty liquid water or soft ice has apparently filled long, deep fractures in the crust. Large blocks of ice float like rafts across Europa's surface, lubricated by warm, slushy material. A subsurface ocean of liquid water may therefore lie just beneath Europa's icy crust, perhaps even harboring alien life that thrives in the dark warmth. Ganymede has an intrinsic magnetic field. As far as we know, it is the only satellite known that now generates its own magnetism. Callisto is one of the oldest, most heavily cratered surfaces in the solar system. Both Callisto and Europa have a borrowed magnetic field, apparently generated by electrical currents in a subsurface ocean as Jupiter's powerful field sweeps by.

Our voyage of discovery continues in Chapter 10 with Saturn, second only to Jupiter in size. Like Jupiter, the ringed planet radiates almost twice as much energy as it receives from the Sun, but Saturn is not massive enough to have substantial heat left over from its formation. Its excess heat is generated by helium raining down inside the planet. It is Saturn's fabled rings that set the planet apart from the other wanderers. The astonishing rings consist of billions of small, frozen particles of water ice, each in its own orbit around Saturn like a tiny moon. They have been arranged into rings within rings by the gravitational influences of small nearby satellites that generate waves, sweep out gaps and confine the particles in the rings. Saturn's rings are thought to be relatively young, less than 100 million years old. They may have originated when a former moon strayed too close to the planet and was torn apart by its tidal forces.

Saturn's largest satellite, Titan, has a substantial atmosphere composed mainly of nitrogen molecules, also the principal ingredient of Earth's air. Clouds of methane, raining ethane, and flammable seas of ethane, methane and propane could exist beneath the impenetrable haze. We should find out what lies beneath the smog when the *Cassini* spacecraft arrives at Saturn, in July 2004, and parachutes the *Huygens* probe through Titan's atmosphere four months later. Six medium-sized moons revolve around Saturn, each covered with water ice. They are scarred with ancient impact craters, and some of them show signs of ice volcanoes and internal heat. A number of small irregularly shaped moons of Saturn have remarkable orbits. The co-orbital moons move in almost identical orbits, the Lagrangian moons share their orbit with a larger satellite, and the shepherd moons confine the edges of rings.

Uranus and Neptune are treated together in Chapter 11, because of their similar size, mass and composition. Unlike all the other planets, Uranus is tipped on its side and rotates with its spin axis in its orbital plane and in the opposite direction to that of most of the other planets. No detectable heat is emitted from deep inside Uranus, while Neptune emits almost three times the amount of energy it receives from the Sun. This internal heat drives Neptune's active atmosphere, which has fierce winds and short-lived storms as big as the Earth. Both planets are vast global oceans, consisting mainly of melted ice with no metallic hydrogen inside. The magnetic fields of both Uranus and Neptune are tilted from their rotation axes, and are probably generated by currents in their watery interiors. The ring systems of both planets are largely empty space, containing dark narrow rings with wide gaps. One of Neptune's thin rings is unexpectedly lumpy, with material concentrated in clumps by a nearby moon. The rings we now see around these planets will eventually be ground into dust and vanish from sight, but they can easily be replaced by debris blasted off small moons already embedded in them. The amazingly varied landscape on Miranda, the innermost mid-sized satellite of Uranus, indicates that the satellite may have been shattered by a catastrophic collision and reassembled, or else it was frozen into an embryonic stage of development. Neptune's satellite Triton revolves about the planet in the opposite direction to its spin. The glazed satellite has a very tenuous, nitrogen-rich atmosphere, bright polar caps of nitrogen and methane ice, frozen lakes flooded by past volcanoes of ice, and towering geysers that may now be erupting on its surface. Triton may have formed elsewhere in the solar system and was captured into obit around Neptune. Triton is headed for a future collision with Neptune as the result of tidal interaction with the planet.

Chapter 12 discusses the icy comets. They light up and become visible for just a few weeks or months when tossed near the Sun, whose heat vaporizes the comet's surface and it grows large enough to be seen. A million, million comets are hibernating in the deep freeze of outer space, and they have been out there ever since the formation of the solar system 4.6 billion years ago. We can detect some of them in the Kuiper belt reservoir at the edge of the planetary system, but billions of unseen comets reside in the remote Oort cloud nearly halfway to the nearest star. Two spacecraft have now passed close enough to image a comet nucleus, of Comet Halley and Comet Borrelly, showing that they are just gigantic, black chunks of water ice, other ices, dust and rock, about the size of New York City or Paris. When these comets come near the Sun, their icy nuclei release about a million tons of water and dust every day, from fissures in their dark crust. Some comets develop tails that flow away from the Sun, briefly attaining lengths as large as the distance between the Earth and the Sun, but other comets have no tail at all. Comets can have two kinds of tails: the long, straight, ion tails, that re-emit sunlight with a faint blue fluorescence, and a shorter, curved, dust tail that shines by reflecting yellow sunlight. They are blown away from the Sun by its winds and radiation, respectively. Meteor showers, commonly known as shooting stars, are produced when sand-sized or pebble-sized pieces of a comet burn up in the Earth's atmosphere, never reaching the ground. Any comet that has been seen will vanish from sight in less than a million years, either vaporizing into nothing or leaving a black, invisible rock behind. Some burned-out comets look like asteroids, and a few asteroids behave like comets, blurring the distinction between these two types of small solar-system bodies.

We continue in Chapter 13 with the rocky asteroids. There are billions of them in the main asteroid belt, located between the orbits of Mars and Jupiter, but they are so small and widely spaced that a spacecraft may safely travel though the belt. The combined mass of billions of asteroids is less than five percent of the Moon's mass. The Earth resides in a smaller swarm of asteroids, chaotically shuffled out of the main belt. Many of these near-Earth asteroids travel on orbits that intersect the Earth's orbit, with the possibility of an eventual devastating collision with our planet. The asteroids are the pulverized remnants of former, larger worlds that failed to coalesce into a single planet. The colors of sunlight reflected from asteroids indicate that they formed under different conditions prevailing at varying distance from the Sun. We could mine some of the nearby ones for minerals or water. An asteroid's gravity is too weak to hold on to an atmosphere or to pull most asteroids into a round shape. The close-up view obtained by passing spacecraft and radar images indicates that asteroids have been battered and broken apart during catastrophic collisions in years gone by. One spacecraft has circled the near-Earth asteroid 433 Eros for a year, examining its dusty, boulder-strewn landscape in great detail, obtaining an accurate mass for the asteroid, and showing that much of it is solid throughout. Other asteroids are rubble piles, the low-density, collected fragments of past collisions held together by gravity. Meteorites are rocks from space that survive their descent to the ground, and most of them are chips off asteroids. Organic matter found in meteorites predates the origin of life on Earth by a billion years; but the meteoritic hydrocarbons are not of biological origin.

The concluding Chapter 14 discusses colliding worlds, including pieces of a comet that hit Jupiter, comets that are on suicide missions to the Sun, and an asteroid that wiped out the dinosaurs when it hit the Earth 65 million years ago. The Earth is now immersed within a cosmic shooting gallery of potentially lethal, Earth-approaching asteroids and comets that could collide with our planet and end civilization as we know it. The lifetime risk that you will die as the result of an asteroid or comet striking the Earth is about the same as death from an airplane crash, but a lot more people will die with you during the cosmic impact. It could happen tomorrow or it might not occur for hundreds of thousands of years, but the risk is serious enough that astronomers are now taking a census of the threatening ones. With enough warning time, we could redirect its course.

The Cambridge Guide to the Solar System continues with an annotated list of books for further reading, all published after 1990, and a list of Internet addresses for the topics discussed.

The illustrator Sue Lee has combined artistic talent with a scientist's eye for detail in producing the fantastic line drawings and diagrams in this book. The text has been substantially improved by the careful attention of copy-editor Brian Watts.

This book was stimulated by the author's visit to the Jet Propulsion Laboratory, when the main results of the recent planetary missions were summarized by its director, Edward C. Stone, and the Project Scientists of many of them. Andrew P. Ingersoll, Torrence V. Johnson, Kenneth Nealson, R. Stephen Saunders, Donald K. Yeomans and Richard W. Zurek provided comprehensive scientific summaries matched only by the extraordinary accomplishments of the missions themselves. Planetary scientists with comprehensive knowledge have assured the accuracy, completeness and depth of individual chapters through critical review. I am grateful to my expert colleagues who have read portions of this book, and substantially improved it, either by thorough review or by expert commentary

on some isolated sections. They include Reta Beebe, Doug Biesecker, Mark A. Bullock, Owen K. Gingerich, Torrence V. Johnson, Brian G. Marsden, Steven J. Ostro, Carl B. Pilcher, Roger A. Phillips, David Senske, Paul D. Spudis, David J. Stevenson and Donald K. Yeomans.

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Principal units

This book uses the International System of Units (Système International, SI) for most quantities, but with two exceptions. As is the custom with planetary scientists, we often use the kilometer unit of length and the bar unit of pressure. The familiar kilometer appears on most automobile speedometers. There are one thousand meters in a kilometer, and a mile is equivalent to 1.6 kilometers. One bar corresponds to the surface pressure of the Earth's air at sea level. For conversion to the SI pressure unit of pascals, 1 bar $= 10^5$ pascals, or 1 pascal $= 10^{-5}$ bar.

Some other common units are the millibar, equivalent to 0.001 bar, the nanometer (nm) with 1 nm $= 10^{-9}$ meters, the micron or micrometer (μm) with 1 μm $= 10^{-6}$ m, the ångstrom unit of wavelength, where 1 ångstrom = 1 Å $= 10^{-10}$ meters, the nanotesla (nT) unit of magnetic flux density, where 1 nT $= 10^{-9}$ tesla $= 10^{-5}$ gauss, and the ton measurement of mass, where 1 ton $= 10^3$ kilograms $= 10^6$ grams.

The reader should also be warned that centimeter-gram-second (c.g.s.) units have been, and still are, widely employed in astronomy and astrophysics. The table provides unit abbreviations and conversions between units.

Quantity	SI units	Conversion to c.g.s. units
Length	meter (m)	100 centimeters (cm)
Mass	kilogram (kg)	1000 grams (g)
Time	second (s)	
Temperature	kelvin (K)	
Velocity	meter per second ($m\ s^{-1}$)	100 centimeters per second ($cm\ s^{-1}$)
Energy	joule (J)	10 000 000 erg
Power	watt (W) = joule per second ($J\ s^{-1}$)	10 000 000 erg s^{-1} (= 10^7 erg s^{-1})
Magnetic flux density	tesla (T)	10 000 gauss (G) (= 10^4 G)
Force	newton (N) (= $kg\ m\ s^{-2}$)	100 000 dyn (= 10^5 dyn)
Pressure	pascal (Pa) (= $N\ m^{-2}$) (= $kg\ m^{-1}\ s^{-2}$)	10 dyn cm^{-2} (= 10^{-5} bar)