Planetary Sciences

Updated Second Edition

An authoritative introduction for graduate students in the physical sciences, this award-winning textbook explains the wide variety of physical, chemical, and geological processes that govern the motions and properties of planets.

This updated second edition has been revised and improved with data that are current as of mid 2014, while maintaining its existing structure and organization. Many data tables and plots have been updated to account for the latest measurements. A new Appendix G focuses on recent discoveries since the second edition was first published (2010), compiled in chapter order. These include results from Cassini, Kepler, MESSENGER, MRO, LRO, Dawn at Vesta, Curiosity, and others, as well as many ground-based observatories.

With over 300 exercises to help students apply the concepts covered, this textbook is ideal for graduate courses in astronomy, planetary science, and earth science, and well suited as a reference for researchers. Color versions of many figures, movie clips supplementing the text, and other resources are available at www.cambridge.org/depater.

Imke de Pater is a Professor in the Astronomy Department and the Department of Earth and Planetary Science at the University of California, Berkeley, and is affiliated with the Faculty of Aerospace Engineering at the Delft University of Technology, the Netherlands. She began her career observing and modeling Jupiter's synchrotron radiation followed by detailed investigations of the planet's atmosphere. In 1994, she led a worldwide campaign to observe the impact of Comet D/Shoemaker–Levy 9 with Jupiter. Currently, she is exploiting adaptive optics techniques in the infrared range to use high angular resolutions data to study the giant planets with their ring and satellite systems.

Jack J. Lissauer is a Space Scientist at NASA's Ames Research Center in Moffett Field, California, and a Consulting Professor at Stanford University. His primary research interests are the formation of planetary systems, detection of extrasolar planets, planetary dynamics and chaos, planetary ring systems, and circumstellar/protoplanetary disks. He is lead discoverer of the six-planet Kepler-11 system and co-discoverer of the first four planets found to orbit about faint M dwarf stars, and co-discovered two broad tenuous dust rings and two small inner moons orbiting the planet Uranus.

Planetary Sciences received the Chambliss Astronomical Writing Award for 2007. This is an award given by the American Astronomical Society (AAS) for astronomy books for an academic audience, specifically textbooks at either the upper division undergraduate level or the graduate level.

Front Cover: Artist's conception of a protoplanetary disk. A growing giant planet appears in the foreground (lower right). This planet has a massive atmosphere, and it has partially cleared a gap around its orbit via gravitational torques (see Chapters 11 and 13). It is accreting both gas and small planetesimals; the latter shed material as they fall into the planet's atmosphere and look like comets. Numerous lunar-sized planetary embryos within the disk are visible through the gravitational wakes that they create in the disk of small planetesimals; such wakes have been observed in Saturn's rings. A pair of these bodies has just collided and glows red. The star at the center of the disk is in its final stages of accretion, and is expelling gas through a bipolar wind. The disk near the star is warmed by both starlight and viscous dissipation within the disk itself; both processes provide more energy closer to the center of the disk. The blue shading of the outer disk is intended to give the impression of cool temperatures, but in reality such regions would appear dark red; similarly, the radially symmetric structure in the disk has been exaggerated in order to convey the impression of rotation. The top of the painting shows other young stars and interstellar gas and dust that inhabit the same stellar nursery as the star/disk system seen close-up. Painted by Lynette Cook (www.lynettecook.com) in 1999, with scientific consultation of Jack Lissauer.

Back Cover: Panoramic view of Saturn, created by combining 165 images taken by the wide-angle camera on the Cassini spacecraft in September 2006. The mosaic images were acquired while the spacecraft was in Saturn's shadow, and hence the rings are seen in forward scattered light. Such a viewing geometry enhances light from microscopic grains. The G ring is easily seen here, outside the bright main rings, while the extended E ring encircles the entire system. Enceladus appears as a white dot within the E ring in the lower left portion of the figure, and Earth is the pale blue dot just inside the G ring in the upper left. (Based on PIA08329, NASA/JPL/SSI/M. Hedman, M. Fondeur and F. van Breugel.)

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Preface to the First Edition

The study of Solar System objects was the dominant branch of Astronomy from antiquity until the nineteenth century. Analysis of planetary motion by Isaac Newton and others helped reveal the workings of the Universe. While the first astronomical uses of the telescope were primarily to study planetary bodies, improvements in telescope and detector technology in the nineteenth and early twentieth centuries brought the greatest advances in stellar and galactic astrophysics. Our understanding of the Earth and its relationship to the other planets advanced greatly during this period. The advent of the Space Age, with lunar missions and interplanetary probes, has revolutionized our understanding of our Solar System over the past forty years. Dozens of planets in orbit about stars other than our Sun have been discovered since 1995; these massive extrasolar planets have orbits quite different from the giant planets in our Solar System, and their discovery is fueling research into the process of planetary formation.

Planetary Science is now a major interdisciplinary field, combining aspects of Astronomy/Astrophysics with Geology/Geophysics, Meteorology/Atmospheric Sciences, and Space Science/Plasma Physics. We are aware of more than ten thousand small bodies in orbit about the Sun and the giant planets. Many objects have been studied as individual worlds rather than merely as points of light. We now realize that the Solar System contains a more dynamic and rapidly evolving group of objects than previously imagined. The cratering record on dozens of imaged bodies shows that impacts have been quite important in the evolution of the Solar System, especially during the epoch of planetary formation. Other evidence, including the compositions of meteorites and asteroids and the high bulk density of the planet Mercury, suggests that even more energetic collisions have disrupted objects. More modest impacts, such as the collision of comet D/Shoemaker–Levy 9 with Jupiter in 1994, continue to occur in the current era. Dynamical investigations have destroyed the regular 'clockwork' image of the Solar System that had held prominence since the time of Newton. Resonances and chaotic orbital variations are now believed to have been important for the evolution of many small and possibly some large planetary bodies.

The renewed importance of the Planetary Sciences as a subfield of Astronomy implies that some exposure to Solar System studies is an important component to the education of astronomers. Planetary Sciences' close relationship to Geophysics, Atmospheric and Space Sciences means that the study of the planets offers the unique opportunity for comparison available to Earth scientists.

The amount of material contained in this book is difficult to cover in a one year graduate-level course. Moreover, many professors will prefer to cover their favorite topics at greater depth using supplemental materials. Most students using this book are likely to be taking one semester classes, and many will be undergraduates. Although many superficially differing aspects of the Planetary Sciences are interconnected, and we have included extensive cross-referencing between chapters, we have also attempted to organize the text in a manner that allows for courses to focus on more limited topics. Chapter 1 and the first sections of Chapters 2 and 3 should be covered by all students. The remainder of Chapter 2 is particularly useful for Chapters 9–13, and is essential for Chapter 11 and portions of Chapter 12. The remainder of Chapter 3 is essential for Chapter 4 and useful for Chapters 5, 6, 9, and 10. Portions of Chapter 5 are needed for Chapter 6. Chapter 7 is probably the most technical. Chapter 8 contains necessary material for Chapters 9 and 12, and parts of Chapters 9 and 10 are closely related. Although details of observing techniques are beyond the scope of this book, we think it is important that the students are familiar with the variety of observational methods. We have therefore included a general summary of observational techniques in Chapter 9.

Various symbols are commonly used to represent variables and constants in both equations and the text. Some variables have a unique correspondence with standard symbols in the literature, whereas other variables are represented by differing symbols by different authors and many symbols have multiple uses. The interdisciplinary nature of the Planetary Sciences exacerbates the problem because standard notation differs between fields. We have endeavored to minimize confusion within the text and provide the student with the greatest access to the literature by using standard symbols, sometimes augmented by non-standard subscripts or printed using calligraphic fonts in order to avoid duplication of meanings whenever practical. A list of the symbols used in this book is presented as Appendix A.

Inclusion of high-quality color figures within the main text would have added substantially to this book's production costs and consequently to its price. We have thus used monochrome illustrations wherever possible and included color plates in a separate section. However, to facilitate the flow of figures in the book, we have included a monochrome representation and the figure caption within the main text, with the color image and figure number presented in the plates.

We feel that the learning of concepts in the physical sciences, as well as obtaining a feel for Solar System properties, is greatly enhanced when students get their 'hands dirty' by solving problems. Thus, we have included an extensive collection of exercises at the end of each chapter in this text. We rank these problems by degree of conceptual difficulty: The easiest problems, denoted by E, should be accessible to most upper level undergraduate science majors; indeed, some are simply plugging numbers into a given formula. Intermediate (I) problems involve more sophisticated reasoning, and are geared towards graduate students. Some of the difficult (D) problems are quite challenging. Note that these rankings are not related to the number of calculations required, and some E problems take most graduate students longer to solve than some of the I problems.

The breadth of the material covered in the text extends well beyond the area of expertise of the authors. As such, we benefited greatly from comments by many of our colleagues. Especially useful suggestions were provided by Michael A'Hearn, James Bauer, Alice Berman, Donald DePaolo, John Dickel, Luke Dones, Martin Duncan, Stephen Gramsch, Russell Hemley, Bill Hubbard, Donald Hunten, Andy Ingersoll, Raymond Jeanloz, David Kary, Monika Kress, Typhoon Lee, Janet Luhmann, Geoffrey Marcy, Jay Melosh, Bill Nellis, Eugenia Ruskol, Victor Safronov, Mark Showalter, David Stevenson, John Wood, and Dorothy Woolum. Our special thanks go to Catherine Flack, our initial editor, who helped make the book more readable. We enjoyed discussions and comments by the students who were taught with drafts of book chapters, and who worked through half-baked problem sets. This book, like the rapidly evolving field of Planetary Sciences, is a work in progress; as such, we welcome corrections, updates, and other suggestions that we may use to improve future editions. Cambridge University Press has set up a web page for this book on their website: www.cup.cam.ac.uk/scripts/textbook.asp. This page includes errata, various updates, color versions of some of the figures that appear in black and white in this volume, and links to various Solar System information sites.

We dedicate this book to our parents and teachers, and to family, friends, and colleagues who provided us encouragement and support over many years, and to Floris van Breugel, now a teenager, who has never known his mother *not* to be working on this book.

Imke de Pater and Jack J. Lissauer
Berkeley, California
December, 1999

Preface to the Second Edition

Humanity's knowledge (and, hopefully, understanding) of our Solar System has increased by leaps and bounds since the first edition of *Planetary Sciences* was written and published, and data on extrasolar planets have increased manifold. We have thus substantially revised and updated many parts of this text. But the primary purpose of this book remains the same as when we first conceived of it two decades ago: To provide the student/reader with a broad-based introduction to planetary sciences at a level sufficiently high to understand relationships between planetary sciences and related disciplines, to make most of the research literature accessible, and to have the background for teaching planetary sciences at the introductory level. Many researchers (including ourselves!) also find it very useful as a ready reference to planetary processes and data.

When we submitted the manuscript of the first edition for publication, we tabulated the basic physical and orbital properties of all known planetary satellites; by the time that we were reviewing proofs, almost two dozen more small outer moons of Jupiter and Saturn had been discovered, and we referred to the new bodies only as groups. The number of newly discovered small moons is now so large that, even though we have increased the length of the table of satellite orbital properties, only about half of the known moons are included.

Hundreds of Kuiper belt objects have now been studied as individual physical bodies, and therefore we have moved our discussion of this population from Chapter 10 (Comets) to Chapter 9 (formerly called Asteroids, now named Minor Planets), although the dynamics of the transfer of these bodies to the inner Solar System where they exhibit cometary activity remains in Chapter 10. Oort cloud objects have not yet been observed *in situ*, so we continue to include the Oort cloud in Chapter 10.

The first extrasolar planets were discovered while we were writing the first edition of this text. We included this topic as an afterthought in a short final chapter. Substantially more about exoplanets is now known, and this body of knowledge now comprises important clues and constraints about the process of planetary formation. Thus, we have moved the discussion of exoplanets to Chapter 12, prior to covering planetary formation, which is now done in Chapter 13.

The appendices have been substantially enhanced for this edition. Acronyms are common in our field, so we now list the ones used in this book in Appendix B. Some key observing techniques are discussed in the new Appendix E; emphasis is placed on methods used more frequently in studying Solar System bodies apart from the Sun and Earth than in astronomy of more distant objects or geology; techniques specific to certain types of objects, e.g., small bodies and extrasolar planets, are discussed within the appropriate chapters. As the resurgence in planetary studies during the past half century is due primarily to spacecraft sent to make close-up observations of distant bodies, we introduce rocketry and list the most significant lunar and planetary missions in Appendix F. Last but not least, as planetary science is a rapidly advancing field, Appendix G shows a selection of Solar System images released in 2009; we plan to update this appendix with a summary of recent developments in future printings.

The use of the world wide web has increased substantially in recent years. For the first edition, we posted only an erratum on the web. The book's website, www.cambridge.org/depater now includes downloadable versions of many of the figures in this book, many of which are in color, as well as some in movie format. Captions to figures with associated movies on the website are indicated in the margin by , and those for figures in color on the website by .

We have benefited greatly from comments on the first edition and draft chapters of the second edition from many students and colleagues. Substantial parts of the text, and many of the problems at the ends of the chapters, have been revised, clarified, and/or updated. Particularly helpful suggestions were provided by Dana Backman, Bill Bottke, Dave Brain, Mike DiSanti, Tony Dobrovloskis, Denton Ebel, Alison Farmer, Bill Feldman, Jonathan Fortney, Richard French, Pat Hamill, Joop Houtkooper, Olenka Hubickyj, Wing Ip, Margaret Kivelson, Rob Lillis, Mark Marley, Paul Mahaffy, Hap McSween, Julie Moses, Francis Nimmo, Larry Nittler, Dave O'Brien, Kaveh Pahlevan, Derek Richardson, Adam Showman, Steve Squyres, Glen Stewart, Chad Trujillo, Len Tyler, Bert Vermeersen, Kees Welten, Josh Winn, Kevin Zahnle and many of the individuals acknowledged above for their assistance in preparing the first edition.

Imke de Pater and Jack J. Lissauer
Berkeley, California
1 May 2009

Preface to the Updated Second Edition (2015)

Planetary sciences is an active research field, and our knowledge of the planets and smaller bodies in the Solar System is increasing very rapidly. The newer discipline of exoplanet research is expanding at an even faster pace. Thus, no compendium on this subject can be completely up to date. In this updated printing, we have corrected errors, revised tables, and in some cases provided updated figures within the main text. Substantial new material, which would require repagination of the main text leading to higher textbook cost, is presented in Appendix G.