

Physical Processes in the Solar System

An introduction to the physics
of asteroids, comets, moons and planets

First Edition

John D. Landstreet
University of Western Ontario
London, Canada

PUBLISHED BY KEENAN & DARLINGTON, PUBLISHERS,
18 Rollingwood Circle, London, Ontario, Canada N6G 1P7

KEENAN & DARLINGTON, PUBLISHERS
18 Rollingwood Circle, London, Ontario, Canada N6G 1P7
e-mail: planets@corcaroli.astro.uwo.ca
Web: <http://www.astro.uwo.ca/~jlandstr/planets>

Copyright © John D. Landstreet 2003. All rights reserved.

This book is copyright. Subject to statutory exception, and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of the publisher.

Front cover: Comet Hyakutake; back cover: Comet Hale-Bopp.
Cover images copyright © Dominique Dierick, Gent, Belgium. Used by permission.

First published 2003

Printed in Canada

This book was prepared with the \LaTeX document preparation system.

National Library of Canada Cataloguing in Publication

Landstreet, John D., 1940-

Physical processes in the solar system: an introduction to the origin, structure and evolution of asteroids, comets, planets and moons / John D. Landstreet.

Includes bibliographical references and index.

ISBN 0-9732051-0-5

1. Solar system -- Textbooks. I. Title. QB 501.L35 2003

523.2

C2003-903439-9

ISBN 0-9732051-0-5 paperback

Contents

Preface	vii
1 A Survey of the Solar System	1
1.1 Overview	1
1.2 An inventory of the solar system	3
1.3 Planetary sizes, separations, and motions	11
1.4 Gravitation	24
1.5 Tides	27
1.6 Mathematical aspects	28
1.7 References	32
1.8 Review questions	33
1.9 Problems	33
2 Matter and its Atomic Structure	35
2.1 Overview	35
2.2 Atomic nature of matter	35
2.3 States of matter	45
2.4 Chemical bonds	51
2.5 Minerals	54
2.6 Rocks	58
2.7 Mathematical aspects	60
2.8 References	63
2.9 Review questions	63
2.10 Problems	63
3 The Sun and the Astronomical Environment	65
3.1 Overview	65
3.2 The Milky Way galaxy	65
3.3 Structure of main sequence stars	68
3.4 Stellar evolution and the synthesis of heavy elements	72
3.5 The star in the solar system: the Sun	76
3.6 Mathematical aspects	86
3.7 References	92
3.8 Review questions	92
3.9 Problems	93
4 Formation of Stars and Planetary Systems	95
4.1 Introduction	95
4.2 How star formation occurs	95
4.3 Formation of planetary systems	99
4.4 Formation of planetary bodies	101
4.5 Detection of planet systems around other stars	103
4.6 Mathematical aspects	105

4.7	References	109
4.8	Review questions	109
4.9	Problems	110
5	Meteors, Impacts, and Meteorites	113
5.1	Overview	113
5.2	Collisions of the Earth with space debris	114
5.3	Meteors	114
5.4	Impact craters on the Earth	119
5.5	Meteorite types and parent bodies	123
5.6	Chondritic meteorites	124
5.7	Differentiated meteorites	128
5.8	Information about the solar nebula from chondrites	130
5.9	Dating meteorites: the age of the solar system	134
5.10	Mathematical aspects	137
5.11	References	141
5.12	Review questions	142
5.13	Problems	142
6	Asteroids	cxlv
6.1	Overview	cxlv
6.2	Discovery	cxlv
6.3	Orbits	cxlvi
6.4	Physical nature of asteroids	cxlix
6.5	Origin and evolution of asteroids	clix
6.6	Mathematical aspects	clxv
6.7	References	clxx
6.8	Review questions	clxx
6.9	Problems	clxxi
7	Comets	173
7.1	Overview	173
7.2	Orbital behaviour of comets (and a little history)	173
7.3	Comet nuclei, comas, and tails	176
7.4	Space probes to Comet Halley	186
7.5	Origin and evolution of comets	188
7.6	Mathematical aspects	194
7.7	References	200
7.8	Review questions	201
7.9	Problems	201
8	The Earth	203
8.1	Overview	203
8.2	The interior of the Earth	203
8.3	The dynamic Earth and drifting continents	211
8.4	Origin and early evolution of the Earth	219
8.5	Mathematical aspects	223
8.6	References	226
8.7	Review questions	227
8.8	Problems	227

9 Other Terrestrial Planets	229
9.1 The Earth's Moon	229
9.2 Impacts and craters, again	236
9.3 Mercury	239
9.4 Mars	243
9.5 Venus	253
9.6 The terrestrial planets: a final comparison	259
9.7 Mathematical aspects	260
9.8 References	260
9.9 Review questions	262
9.10 Problems	262
10 Terrestrial Planetary Atmospheres	265
10.1 Overview	265
10.2 Variation of pressure and density with height	267
10.3 The temperature of the atmosphere	268
10.4 Variations of temperature with height	271
10.5 Motions in the atmosphere	273
10.6 The atmosphere of Venus	278
10.7 The atmosphere of Mars	280
10.8 The origin of the atmospheres of the inner planets	282
10.9 Evolution of the terrestrial atmospheres	285
10.10 Mathematical aspects	290
10.11 References	292
10.12 Review questions	293
10.13 Problems	293
11 Giant Planets and their Moons	ccxcv
11.1 Overview	ccxcv
11.2 The giant planets	ccxcvi
11.3 Moons of the giant planets	cccix
11.4 Planetary ring systems	cccxxvii
11.5 Pluto and Charon	cccxxxi
11.6 Mathematical aspects	cccxxxiii
11.7 References	cccxxxvi
11.8 Review questions	cccxxxvii
11.9 Problems	cccxxxvii
A Characteristics of planets and moons	341
B Physical and astronomical constants	343

Preface

This book is an attempt to create an up-to-date text on the physics of the solar system and the objects that make it up. It thus has a rather different outlook compared to books that focus on descriptive material, on geological ideas, or on chemistry and astro-biology, although aspects of all these approaches do appear in the book. I have tried to centre the discussions on the big ideas, on how things work, on what the structure and history of various bodies has been, and on why we accept some answers to our questions and reject others. Because of this approach, the book does not provide a complete survey of the enormous amount of information now available about solar system objects. Instead I have concentrated on subjects that are thought to be (at least qualitatively) understood at present, and particularly on topics that illustrate the application of physical ideas and reasoning.

The material is examined in two different ways in each chapter: first, the subject of the chapter is discussed qualitatively and conceptually, and then towards the end of the chapter some of the same material is re-analyzed quantitatively using the tools of first year university physics and calculus. The reason for this double approach is connected with the kinds of student who took the one-semester course on “Solar System Physics” that I offered at the University of Western Ontario for a number of years, and for whom this book was written. The course originated as a part of the Astronomy Honours (four-year B. Sc.) programme at the university, and was initially designed around the goals of (a) familiarizing the students with the wide range of aspects of the solar system that can be understood using the material from the first year of university physics, and (b) using the solar system to solidify the students’ mastery of that physics. I have found that the solar system provide a wonderful variety of questions that can be discussed using first-year physics, and that a course discussing such problems is very effective at helping students to realize the power of even one year of physics for understanding natural phenomena in their environment.

However, I soon discovered that a number of students other than those in honours physics or astronomy programmes were interested in taking the course. Many of these other students lacked the background in physics

needed to solve the problems that formed an important part of our course, and so I developed a second version of the same solar system course, which emphasizes qualitative understanding of concepts, ability to reason with these concepts, and practice explaining basic ideas through a series of essays submitted through the semester. The only prerequisite I imposed for entrance to this more qualitative version of the course was successful completion of any first year university physical science course (astronomy, chemistry, geology, or physics, qualitative or quantitative) so that I could assume that the students would have some prior knowledge of such topics as conservation of energy and the structure of atoms.

Because of limited teaching resources, it was always necessary to teach these two versions of the course together. Thus I have tried to create a single text which could be used by both groups. Conceptual but qualitative material forms the bulk of each chapter; I found that this material could be presented in a manner that is reasonably intelligible to and appropriate for both groups, although students with different backgrounds certainly understand the material in somewhat different ways. The students in the essay version of the course read only these (non-mathematical) sections of the book. To allow the students to test their understanding of the reading as they progress, small exercises are embedded in the text, and review questions are included at the end of each chapter.

To help the students in the problem-solving course to see more clearly how the university physics they have learned may be applied to understanding the solar system, each chapter ends with a section called “Mathematical aspects”, in which relevant aspects of first-year physics are reviewed (and perhaps extended), some of the most interesting applications of quantitative physics are discussed, and useful tools for analysis of problems are presented. The students in the problem-solving course read this section, as well as the rest of each chapter. Each chapter has a number of quantitative short exercises in the “Mathematical aspects” section, and students in the problem-solving group are encouraged to do all of these as they come to them. In addition, there is a selection of more challenging problems at the end of each chapter for this

group; most of these are conceptually interesting problems rather than the “plug-in” type.

This system of offering two courses in one package has worked quite well, probably because any course on the solar system involves introduction of a very large number of unfamiliar ideas which need to be thought about and discussed qualitatively before they are understood – and before interesting problems can be solved. I have two classes a week for all the students, in which we discuss the big ideas of that week’s reading, and a third (tutorial) class for the students in the problem-solving group, devoted mainly to discussion of the use of physics and of problem-solving in the course context. Assignments for the essay course are a series of (usually three) essays on solar system topics, based on the text and supplementary reading. The students in the problem-solving course do a series of problem sets, taken from problems collected at the end of each chapter. Tests and examinations are partly the same for both versions of the course, but the essay course has a number of essay questions on each test which are replaced by short conceptual problems for the problem-solving group.

To encourage the students to learn more about topics of interest, and to help them find suitable subjects for essays, each chapter also includes a short bibliography listing resources that I have found particularly useful. However, since each chapter’s bibliography is specific to the subject of the chapter, let me mention a few general solar system texts that may be useful to teachers and students. *The New Solar System* (Cambridge: Cambridge University Press, 1999), edited by A. Chaikin, C. C. Peterson, and J. K. Beatty, provides a good general and qualitative description of the solar system, nicely illustrated with many colour photos. The *Encyclopedia of Astronomy and Astrophysics* (Bristol, U. K: Institute of Physics Publishing, 2001) has many well-written articles at a very suitable level; this encyclopedia is also available at many universities over the Web. W. K. Hamblin and E. H. Christiansen’s *Exploring the Planets* (New York, NY: Simon & Schuster, 1995) is a detailed, non-mathematical survey of the geological structure and surface features of the planets in the light of space probe data, with many excellent illustrations. A very good general text on the solar system, with a strong focus on geology, rather less physics, and a little mathematics, is W. K. Hartmann’s *Moons and Planets* (Belmont, CA: Wadsworth, 1999). Hartmann’s book is perhaps nearest in general level and intention to this book. Finally, there are two much more advanced texts, *Physics and Chemistry of the Solar System* by J. S. Lewis (San Diego, CA: Academic Press, 1997) and *Planetary Sciences* by I. de Pater and J. Lissauer (Cambridge: Cambridge University Press,

2001). These two books contain detailed discussions of many physical, chemical, and geological aspects of the solar system. Parts of each book require a knowledge of vector calculus, partial differential equations, and chemical thermodynamics, but other parts offer very readable reviews covering a wide range of topics.

I am grateful to the many people who have helped with the preparation of successive versions of this text over the years. Barbara Landstreet and Anne Brooks typed some of the earlier versions. Tara Sopoco, Sarah Landstreet, and especially Mira Rasche have converted many of the drawings and graphs from rough sketches into clear, handsome illustrations. Successive classes have proof-read the book many times, and offered useful comments. Colleagues, particularly Professor P. Brown, have helped me to find good review material and to understand it. Professor K. Keil (University of Hawaii) and several anonymous reviewers made extremely helpful and constructive suggestions. I thank all of these people. I am also grateful to the developers of Linux, of the Gnu utilities (especially emacs), of the T_EX and L^AT_EX document preparation system, and of the Xmgrace graph tool for the powerful (and free) working environment I have employed to prepare the book. I thank the institutions and individuals from whom I have obtained illustrations, especially NASA with its splendid policy of making all its science images available without copyright restrictions, and Mr Dominique Dierick of Gent, Belgium, who contributed the cover images.. I am grateful to the many scientists who work in this exciting and fascinating field for their efforts to make their ideas accessible to the rest of us. And last but not least, I thank Barbara and Sarah Landstreet for encouraging me to persevere with what has at times seemed to be a never-ending project, and for finally getting the book into print.

I would appreciate having errors of fact, concept or proofreading called to my attention. Please drop me an e-mail at jlandstr@astro.uwo.ca.