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Physics and Chemistry of the Solar System

2nd Edition

太阳系物理与化学

第二版

（影印版）

〔美〕刘易斯（J. S. Lewis）著

北京大学出版社
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序　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，“中外物理学精品书系”力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

“中外物理学精品书系”另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，“中外物理学精品书系”还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套“中外物理学精品书系”的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

“中外物理学精品书系”编委会　主任
中国科学院院士，北京大学教授
王恩哥
2010 年 5 月于燕园

Physics and Chemistry of the Solar System

SECOND EDITION

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Department of Planetary Sciences
University of Arizona
Tucson, Arizona

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Dedication

This book is dedicated to the founders of Planetary Science:
Rupert Wildt, Gerard P. Kuiper, and Harold C. Urey,
whose thoughts roamed the Solar System before spacecraft did.

Foreword

At its original conception, this book was based on the structure, scope, and philosophy of a sophomore/junior level course taught at M.I.T. by the author and Prof. Irwin I. Shapiro from 1969 to 1982. Although the content of that course varied greatly over the years in response to the vast new knowledge of the Solar System provided by modern Earth-based and spacecraft-based experimental techniques, the philosophy and level of presentation remained very much the same. The material was brought up to date in 1994 for publication in 1995, and again updated with many corrections and additions for a revised edition in 1997. This second edition was prepared in 2002 to take advantage of the many recent advances in the study of Mars and small Solar System bodies, the discovery and study of more than 100 extrasolar planets, and more mature analysis of the Galileo Orbiter and probe data on Jupiter and its large satellites.

The timing of the various editions of this book has been influenced by the erratic history of planetary exploration. During the 12 years of 1964–1973 there were 87 launches of lunar and planetary spacecraft, of which 54 were involved in the race to the Moon. In the 29 years since the end of 1973, up to the date of this edition in 2002, there have been only 36 additional launches. Both the United States and the Soviet Union experienced prolonged gaps in their lunar and planetary exploration programs: the American gap in lunar exploration extended from Explorer 49 in 1973 to the launch of Clementine in 1994, and the Russian hiatus in lunar missions has stretched from Luna 24 in 1976 to the present. American exploration of Mars was suspended from the time of the Viking missions in 1975 until the launch of Mars Observer in 1992, and Soviet exploration of Mars, suspended after Mars 7 in 1975, did not resume until the launch of the two ill-fated Phobos spacecraft in 1988. Soviet missions to Venus ceased in 1984.

From 1982 to 1986 there was a gap in the acquisition of planetary data by American spacecraft. This drought was interrupted in 1986 by the Voyager 2 Uranus flyby and by five spacecraft encounters with Halley's comet (two Soviet, two Japanese, and one from the European Space Agency), but the drought again resumed until it was broken by the Voyager 2 Neptune encounter and the Soviet Phobos missions in 1989 and the Magellan mission to Venus in 1990. The launch of the Galileo Orbiter and probe to Jupiter, long scheduled for 1986, was severely delayed by the explosion of the space shuttle orbiter Challenger, the resulting 2-year grounding of the entire shuttle fleet, and the subsequent cancellation of the high-energy Centaur G' upper stage intended for launching heavy planetary missions from the shuttle. The European-American Ulysses solar mission, which was not instrumented for intensive planetary studies, flew by Jupiter in February 1992, returning only data on its magnetic and charged-particle environment. The arrival of Galileo at Jupiter, the Galileo Probe entry into

Jupiter's atmosphere in December 1995, the lengthy Galileo Orbiter survey of the Jovian system, and the resumption of small Mars missions (Pathfinder, Mars Global Surveyor, etc.) by the United States have combined with a flood of space-based (Galileo, Near-Earth Asteroid Rendezvous) and Earth-based observations of near-Earth asteroids and Belt asteroids, and intensive Earth-based study of comets, Centaurs, small icy satellites, and trans-Neptunian objects and the highly successful search for dark companions of nearby stars to reinvigorate the planetary sciences. This new resurgence of planetary exploration, with little prospect of Russian participation, has been helped by the active involvement of Japan's NASDA and the European Space Agency in planning and flying unmanned missions to the Moon, Mars, and Venus. The infusion of new data resulting from these several programs creates the necessity of revising this book

In this book, as in that Planetary Physics and Chemistry course in which it was first conceived, I shall assume that the reader has completed 1 year of university-level mathematics, chemistry, and physics. The book is aimed at several distinct audiences: first, the upper-division science major who wants an up-to-date appreciation of the present state of the planetary sciences for "cultural" purposes; second, the first-year graduate student from any of several undergraduate disciplines who intends to take graduate courses in specialized areas of planetary sciences; and third, the practicing Ph.D. scientist with training in physics, chemistry, geology, astronomy, meteorology, biology, etc., who has a highly specialized knowledge of some portion of this material, but has not had the opportunity to study the broad context within which that specialty might be applied to current problems in this field.

This volume does not closely approximate the level and scope of any previous book. The most familiar texts on the planetary sciences are *Exploration of the Solar System*, by William J. Kaufmann, III (Macmillan, New York, 1978 and later), a nonmathematical survey of the history of planetary exploration; *Moons and Planets*, by William K. Hartmann (Wadsworth, Belmont, California, 1972; 1983; 1993), a scientific tour of the Solar System with high-school-level mathematical content; and *Meteorites and the Origin of Planets*, by John A. Wood (McGraw-Hill, New York, 1968), a fine qualitative introduction that is similarly sparing of mathematics and physics. Several other nonmathematical texts are available, including *Introduction to the Solar System*, by Jeffrey K. Wagner (Saunders, Philadelphia, 1991), *Exploring the Planets*, by W. Kenneth Hamblin and Eric H. Christiansen (Macmillan, New York, 1990), *The Space-Age Solar System*, by Joseph F. Baugher (J. Wiley, New York, 1988), and *The Planetary System*, by planetary scientists David Morrison and Tobias Owen (Addison–Wesley, Reading, Massachusetts, 1988).

Another book, comparable in mathematical level to the present text, is *Worlds Apart*, by Guy J. Consolmagno, S. J., and Martha W. Schaefer (Prentice Hall, Englewood Cliffs, New Jersey, 1994). Though much less detailed than the present work, it is well written and appropriate for a one-semester introductory course on planetary science for science majors. The scope of the present text is broader, and the level higher, than any of these books.

As presently structured, this book is a broad survey of the Solar System suitable for reference use or as background reading for any course in Solar System science. The text may for convenience be divided into three parts. The first of these parts contains Chapter I (Introduction), Chapter II (Astronomical Perspective), Chapter III (General Description of the Solar System), and Chapter IV (The Sun and the Solar Nebula). This first part could be called "General Properties and Environment of our Planetary System." It is roughly equivalent to a brief introductory astronomy book emphasizing the concerns of planetary scientists rather than stellar or galactic astronomers. The second part contains Chapter V (The Major Planets), Chapter VI (Pluto and the Icy Satellites of the Outer Planets), Chapter VII (Comets and Meteors), and Chapter VIII (Meteorites and Asteroids), and might fairly be entitled "The Solar System beyond Mars." The third and final part comprises Chapter IX (The Airless Rocky Bodies: Io, Phobos, Deimos, the Moon, and Mercury), Chapter X (The Terrestrial Planets: Mars, Venus, and Earth), Chapter XI (Planets and Life around Other Stars), and Chapter XII (Future Prospects). This part could be called "The Inner Solar System."

Using this volume as a textbook, a planetary sciences course taught in a trimester setting could use one part each term. In a two-semester program, either an inner solar system emphasis course (parts 1 and 3) or an outer solar system course (parts 1 and 2) could be taught. The most ambitious and intensive program, and the most similar to the way the course was structured at M.I.T., would be to teach parts 2 and 3 in two semesters, reserving most of the material in part 1 for use as reference reading rather than as lecture material.

This book is written in appreciation of the approximately 350 students who took the course at M.I.T., and who unanimously and vocally deplored the lack of a textbook for it. These students included both Consolmagno and Schaefer as cited above. I extend my particular thanks to Irwin Shapiro for his many years of cheerful, devoted, always stimulating, and sometimes hilarious collaboration on our course, and for his generous offer to allow me to write "his" half of the text as well as "mine." I am also pleased to acknowledge the helpful comments and suggestions of dozens of my colleagues, but with special thanks reserved for Jeremy Tatum of the University of Victoria, whose detailed comments and physicist's perspective have been invaluable in the preparation of this second edition.

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I. Introduction

Nature and Scope of the Planetary Sciences

When asked in an interview to give his viewpoint on the frontiers of science, the famous physicist Victor Weisskopf commented that the most exciting prospects fell into two categories, the frontier of size and the frontier of complexity. A host of examples come to mind: cosmology, particle physics, and quantum field theory are clearly examples of the extremes of scale, and clearly among the most exciting frontiers of science. Biology, ecology, and planetary sciences are equally good examples of the frontier of complexity.

When we peruse the essential literature of planetary science, we find that we must, over and over again, come face to face with these same extremes. First, we are concerned with the origin and nuclear and chemical evolution of matter, from its earliest manifestation as elementary particles through the appearance of nuclei, atoms, molecules, minerals, and organic matter. Second, on the cosmic scale, the origin, evolution, and fate of the Universe emerge as themes. Third, we are confronted with the problem of understanding the origin and development of life. In each case, we are brought face to face with the spontaneous rise of extreme complexity out of extreme simplicity, and with the intimate interrelationship of the infinitesimally small and the ultimately large.

Further, our past attempts at addressing these three great problems have shown us that they are remarkably intertwined. The very issue of the origin of life is inextricably tied up with the chemistry of interstellar clouds, the life cycles of stars, the formation of planets, the thermal and outgassing history of planetary bodies, and the involvement of geochemical processes in the origin of organic matter. The connection between life and planetary environments is so fundamental that it has been given institutional recognition: it is not widely known outside the field, but research on the origin of life in the United States is a mandate of the National Aeronautics and Space Administration.

Wherever we begin our scientific pilgrimage throughout the vast range of modern science, we find ourselves forced to adopt ever broader definitions of our field of interest. We must incorporate problems not only on the frontier of complexity, but also from both extreme frontiers of scale. In this way, we are compelled to trespass across many hallowed disciplinary boundaries.

Further, as we seek an evolutionary account of the emergence of complexity from simplicity, we become able to see more clearly the threads that lead from one science to another. It is as if the phenomena of extreme scale in physics existed for the express purpose of providing a rationale for the existence of astronomy.

The other disciplines evolve logically from cosmic events:

The astronomical Universe, through the agency of nuclear reactions inside stars and supernova explosions, populates space with atoms of heavy elements, which are the basis of chemistry.

The course of spontaneous chemical evolution of interstellar matter produces both mineral grains and organic molecules, giving rise to geochemistry and organic chemistry.

Solid particles accrete to form large planetary bodies, and give us geology.

Radioactive elements formed in stellar explosions are incorporated into these planets, giving life to geophysics.

Melting, density-dependent differentiation, and outgassing take place, and atmospheres and oceans appear: petrology, meteorology, and oceanography become possible.

Organic matter is formed, accumulated, concentrated, and processed on planetary surfaces, and biology is born.

Planetary science may then be seen as the bridge between the very simple early Universe and the full complexity of the present Earth. Although it partakes of the excitement of all of these many fields, it belongs to none of them. It is the best example of what an interdisciplinary science should be: it serves as a unifying influence by helping to dissolve artificial disciplinary boundaries, and gives a depth and vibrancy to the treatment of evolutionary issues in nature that transcends the concerns and the competence of any one of the parent sciences. But there is more: planetary science is centrally concerned with the evolutionary process, and hence with people's intuitive notion of "how things work." There is as much here to unlearn as there is to learn.

We, at the turn of the millennium, still live under the shadow of the clockwork, mechanistic world view formulated by Sir Isaac Newton in the 17th century. Even the education of scientists is dedicated first and foremost to the inculcation of attitudes and values that are archaic, dating as they do from Newton's era: viewpoints that must be unlearned after sophomore year. We are first led to expect that the full and precise truth about nature may be extracted by scientific measurements; that the laws of nature are fully knowable from the analysis of experimental results; that it is possible to predict the entire course of future events if, at one moment, we should have sufficiently detailed information about the distribution and motion of matter. Quantum mechanics and relativity are later taught to us as a superstructure on Newtonian physics, not vice versa. We must internally turn our education upside down to accommodate a universe that is fundamentally quantum-mechanical, chaotic, and relativistic, within which our "normal" world is only a special case.

All of these issues come to bear on the central question of the evolution of the cosmos and its constituent parts. Most of us have had a sufficient introduction to equilibrium thermodynamics to know that systems spontaneously relax to highly random, uninteresting states with minimum potential energy and maximum entropy. These are the classical conclusions of J. Willard Gibbs in the 19th century. But very few of us are ever privileged to hear about the development of nonequilibrium thermodynamics in the 20th century, with its treatment of stable dissipative structures, least production of entropy, and systems far removed from thermodynamic equilibrium. Think of it: systems slightly perturbed from equilibrium spontaneously relax to the dullest conceivable state, whereas systems far from equilibrium spontaneously organize themselves into structures optimized for the minimization of disorder and the maximization of information content!

It is no wonder that the whole idea of evolution is so magical and counterintuitive to so many people, and that the critics of science so frequently are able to defend their positions by quoting the science of an earlier century. We often hear expressed the idea that the spontaneous rise of life is as improbable as that a printshop explosion (or an incalculable army of monkeys laboring at typewriters) might accidentally produce an encyclopedia. But have we ever heard that this argument is obsolete nonsense, discredited by the scientific progress of the 20th century? Sadly, there is a gap of a century between the scientific world view taught in our schools and the hard-won insights of researchers on the present forefront of knowledge. The great majority of all people never learn more than the rudiments of Newtonian theory, and hence are left unequipped by their education to deal with popular accounts of modern science, which at every interesting turn is strikingly non-Newtonian. News from the world of science is, quite simply, alien to them. The message of modern science, that the Universe works more like a human being than like a mechanical wind-up toy, is wholly lost to them. Yet it is precisely the fundamental issues of how things work and how we came to be, what we are and what may become of us, that are of greatest human interest. The "modern" artist or writer of the 20th century often asserted modernity by preaching the sterility of the Universe and the alienation of the individual from the world. But this supposed alienation of the individual from the Universe is, to a modern scientist, an obsolete and discredited notion.

The problems of evolutionary change and ultimate origins are not new concerns. Far from being the private domain of modern science, they have long been among the chief philosophical concerns of mankind. Astronomy