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PHYSICS AND CHEMISTRY OF THE SOLAR SYSTEM

John S. Lewis

Physics and Chemistry of the Solar System

SECOND EDITION

John S. Lewis

Department of Planetary Sciences
University of Arizona
Tucson, Arizona

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Physics and Chemistry of the Solar System

SECOND EDITION

This is volume 87 in the
INTERNATIONAL GEOPHYSICS SERIES
A series of monographs and textbooks
Edited by RENATA DMOWSKA, JAMES R. HOLTON, and H. THOMAS ROSSBY
A complete list of books in this series appears at the end of this volume.

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 extra-solar 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 and astrology were the parents of modern science. The earliest human records attest to mankind's perpetual fascination with origins:

> Who knows for certain and can clearly state
> Where this creation was born, and whence it came?
> The *devas* were born after this creation,
> So who knows from whence it arose?
>
> No one knows where creation comes from
> Or whether it was or was not made:
> Only He who views it from highest heaven knows;
> Surely He knows, for who can know if He does not?
>
> *Rigveda* X 129.6–7
> Circa 3000 BC

Such an attitude, reflective of curiosity, inquiry, and suspended belief, is admirably modern. But today, in light of the exploration of the Solar System, we need no longer regard our origins as complete mysteries. We can now use the observational and theoretical tools of modern science to test rival theories for their faithfulness to the way the Universe really is. Some theories, when tested by the scientific method, are found to give inaccurate or even blatantly wrong descriptions of reality and must be abandoned. Other theories seem to be very reliable guides to how nature works and are retained because of their usefulness. When new data arise, theories may need to be modified or abandoned. Scientific theories are not absolute truth and are not dogma: they are our best approximation of truth at the moment. Unlike dogma, scientific theories cannot survive very long without confronting and accommodating the observed facts. The scientific theories of today are secondary to observations in that they are invented—and modified—by human beings in order to explain observed facts. They are the result of an evolutionary process, in which the "most fit" theories (those that best explain our observations) survive. In planetary science, that process has been driven in recent years in part by the discovery and study of several new classes of bodies both within our Solar System and elsewhere. It is the great strength of science (not, as some allege, its weakness) that it adapts, modifies, and overturns its theories to accommodate these new realities. Our plan of study of the Solar System mirrors this reality.

This book will begin with what little we presently know with confidence about the earliest history of the Universe, and trace the evolution of matter and its constructs up to the time of the takeover of regulatory processes on Earth by the biosphere. We introduce the essential contributions of the various sciences in the order in which they were invoked by nature, and build complexity upon complexity stepwise. Otherwise, we might be so overawed by the complexity of Earth, our first view of nature, that we might despair of ever gaining any understanding at all.

This approach should also dispel the notion that we are about to understand everything. It is quite enough to see that there are untold vistas for exploration, and more than enough of the Real to challenge our most brilliant intellects and most penetrating intuitions.

Let us approach the subject matter covered herein with the attitude that there are a number of fundamental principles of nature, of universal scope, that allow and force the evolutionary process. With our senses at the most alert, willing to entertain the possibility of a host of hypotheses, and determined to subject all theories and observations alike to close scrutiny, we are challenged to grasp the significance of what we see. Let us cultivate the attitude that the ultimate purpose of the planetary sciences is to uncover enough of the blueprints of the processes of evolution so that we will be able to design, build, and operate our own planetary system.

Like it or not, we are assuming responsibility for the continued stability and habitability of at least one planet. The scale of human endeavor has now become so large that our wastes are, quite inadvertently, becoming major factors in global balances and cycles. Soon our scope may be the whole Solar System. The responsible exercise of our newly acquired powers demands an understanding and consciousness superior to that which we have heretofore exhibited. Now is the time for us to learn how planets work.

Guide to the Literature

It is difficult, as we have seen above, to draw a tidy line around a particular portion of the scientific literature and proclaim all that lies outside that line to be irrelevant. Still, there are certain journals that are more frequently used and cited by practitioners of planetary science. Every student should be aware both of these journals and the powerful abstracting and citation services now available.

Astronomical observations, especially positional measurements, orbit determinations, and the like that are carried out using Earth-based optical, radio, and radar techniques, are often published in the *Astronomical Journal* (AJ). Infrared spectroscopic and radiometric observations and a broad range of theoretical topics often appear in the *Astrophysical Journal* (ApJ). The most important journals devoted to planetary science in the broad sense are *Icarus* and the *Journal of Geophysical Research* (usually called JGR). Two journals are devoted to relatively quick publication of short related papers: *Geophysical Research Letters* (GRL) and *Earth and Planetary Science Letters* (EPSL). Two general-purpose wide-circulation journals also frequently publish planetary science papers, including special issues on selected topics: these are *Science* and *Nature*. The most important western European journal for our purposes is *Astronomy and Astrophysics*.

Russian research papers frequently appear first (or in prompt translation) in English. The most important Soviet journals are *Astronomicheskii Zhurnal* (*Sov. Astron.* to the cognoscenti), *Kosmicheskii Issledovaniya* (*Cos. Res.*), and *Astron. Vestnik* (*Solar System Research*), all of which appear in English translation with a delay of several months.

Other journals containing relevant research articles include *Physics of the Earth and Planetary Interiors* (PEPI), the *Proceedings of the Lunar and Planetary Science Conferences*, the *Journal of the Atmospheric Sciences* (JAS), *Planetary and Space Science*, *Geochimica et Cosmochimica Acta* (GCA), the Russian-language *Geokhimiya*, *Meteoritics*, *Origins of Life*, and perhaps 50 other journals that are usually a bit far from the center of the field, but overlap its periphery.

Many space scientists keep abreast of the politics and technology of space exploration by reading *Aviation Week and Space Technology* (AW&ST), which often prints future news and juicy rumors.

Very valuable service is also rendered by several review publications, such *as Annual Review of Earth and Planetary Science*, *Space Science Reviews*, *Reviews of Geophysics and Space Physics*, and the *Annual Review of Astronomy and Astrophysics*.

Books on the planetary sciences have an unfortunate tendency to become obsolete during the publication process. Nonetheless, many books have useful coverage of parts of the material in the field, and a number of these are cited at the relevant places in the text.

It is often valuable to track down the history of an idea, or to see what recent publications are following a lead established in a landmark paper of several years ago. For these purposes, every scientist should become familiar with the uses of the *Science Citation Index*. Depending upon one's own particular interests, any of a number of other abstracting services and computerized databases may be relevant. The reader is encouraged to become familiar with the resources of the most accessible libraries. Every research library has *Chemical Abstracts*, *Biological Abstracts*, etc.

For the diligent searcher, there will be an occasional gem captured from the publications of the Vatican Observatory, and surely one cannot claim to be a planetary scientist until one has followed a long trail back to an old issue of the *Irish Astronomical Journal*. Be eclectic: have no fear of journals with Serbian or Armenian names. The contents are most likely in English, or if not, then almost certainly in French, German, or Russian, often conveniently equipped with an English abstract.

Many valuable online services have arisen to speed the exchange of scientific data and theories between interested parties, from professional planetary scientists to scientists in other disciplines to the interested public. Never before in history has so much information from all over the world been available in so immediate—and so undigested—a state. These services come, go, and evolve rapidly. Some will be cited at the appropriate places in the text, but the selective use of Web search engines is a more essential part of online research than knowing this month's hottest Web sites. The hazard of this approach to research is that the opinions of professionals, amateurs, ignoramuses, and fanatical ideologues are all weighted equally, and all equally accessible. Never before in history has so much misinformation and disinformation from all over the world been available to mislead the incautious and the gullible. Know your sources!

But planetary science is a genuinely international endeavor. To make the most of the available resources one must be willing to dig deep, think critically, and keep in contact with colleagues abroad. One must be prepared to face the hardship of back-to-back conferences in Hawaii and Nice; of speaking engagements three days apart in Istanbul and Edmonton; of January trips to Moscow balanced against summer workshops in Aspen. I suppose that this is part of our training as thinkers on the planetary scale.

Numbers in Science

It is assumed that all readers are familiar with scientific notation, which expresses numbers in the format $n.nnnn \times 10^x$. This convention permits the compact representation of both extremely small and extremely large numbers and facilitates keeping track of the decimal place in hand calculations. Thus the number 0.0000000000000000000000000066262, Planck's constant, is written in scientific notation as 6.6262×10^{-27}, and Avogadro's number, 602,220,000,000,000,000,000,000, is written 6.0222×10^{23}. Their product is $6.6262 \times 10^{-27} \times 6.0222 \times 10^{23} = 6.0222 \times 6.6262 \times 10^{23} \times 10^{-27} = 39.904 \times 10^{23-27} = 39.904 \times 10^{-4} = 3.9904 \times 10^{-3}$. In some circumstances, where typographic limitations militate against writing actual superscripts and subscripts (as in some scientific programming languages), scientific notation is preserved by writing the number in the form 3.9904E-03.

Numbers are usually written in a form that suggests the accuracy with which they are known. For example, a wedding guest might say "I have traveled 3000 miles to be here today". The literal-minded, after looking up the