PHYSICS OF THE JOVIAN MAGNETOSPHERE

Edited by A. J. DESSLER
Department of Space Physics and Astronomy
Rice University

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CONTRIBUTORS

Mario H. Acuña
Code 695
Goddard Space Flight Center
Greenbelt, MD 20771

J. K. Alexander
Code 695
Goddard Space Flight Center
Greenbelt, MD 20771

Sushil K. Atreya
Department of Atmospheric and Oceanic Science
Space Research Building
University of Michigan
Ann Arbor, MI 48109

Kenneth W. Behannon
Code 692
Goddard Space Flight Center
Greenbelt, MD 20771

J. W. Belcher
Room 37-695
Massachusetts Institute of Technology
Cambridge, MA 02139

Robert A. Brown*
Lunar and Planetary Laboratory
University of Arizona
Tucson, AZ 85721

T. D. Carr
Department of Astronomy
University of Florida
Gainesville, FL 32611

J. E. P. Connerney
Code 695
Goddard Space Flight Center
Greenbelt, MD 20771

M. D. Desch
Code 695
Goddard Space Flight Center
Greenbelt, MD 20771

A. J. Dessler†
Department of Space Physics and Astronomy
Rice University
Houston, TX 77251

C. K. Goertz
Department of Physics and Astronomy
University of Iowa
Iowa City, IA 52242

Melvyn L. Goldstein
Code 692
Goddard Space Flight Center
Greenbelt, MD 20771

D. A. Gurnett
Department of Physics and Astronomy
University of Iowa
Iowa City, IA 52242

T. W. Hill
Department of Space Physics and Astronomy
Rice University
Houston, TX 77251

S. M. Krimigis
Applied Physics Laboratory
Johns Hopkins University
Laurel, MD 20707

Carl B. Pilcher
Institute for Astronomy
2680 Woodlawn Dr.
Honolulu, HI 96822

* Present address: Space Telescope Science Institute, Homewood Campus, Johns Hopkins University, Baltimore, MD 21218

† Present address: Code ES01, Space Science Laboratory, NASA Marshall Space Flight Center, Huntsville, AL 35812

E. C. Roelof
Applied Physics Laboratory
Johns Hopkins University
Laurel, MD 20707

F. L. Scarf
TRW Systems, Bldg. R1, Rm. 1176
One Space Park
Redondo Beach, CA 90278

A. W. Schardt
Code 660
Goddard Space Flight Center
Greenbelt, MD 20771

Darrell F. Strobel
Code 4780
Naval Research Laboratory
Washington, D.C. 20375

Richard Mansergh Thorne
Department of Atmospheric Sciences
University of California at Los Angeles
Los Angeles, CA 90024

James A. Van Allen
Department of Physics and Astronomy
University of Iowa
Iowa City, IA 52242

Vytenis M. Vasyliunas
Max-Planck-Institut für Aeronomie
D-3411 Katlenburg-Lindau 3
Federal Republic of Germany

FOREWORD

During the early 1960s the dominant emphasis of the space program of the United States was on manned space flight, looking toward landings on the moon and the detailed investigation thereof. Parallel with these activities, but at a much lower level of emphasis, was the development of a national program of planetary exploration. The nearby terrestrial planets Venus and Mars were the most readily accessible. Also, interest in search for extraterrestrial life on Mars provided a strong motivation for landing on its surface an elaborate device called an automated biological laboratory. The mission for accomplishing this was called Voyager, a name that was later changed to Viking. Still later, the name Voyager was adopted for an altogether different planetary mission.

The development of a national program of planetary exploration had many sources and many aspects. But to a very considerable extent, all of these aspects came into focus most clearly within the Space Science Board (SSB) of the National Academy of Sciences and more specifically within the National Aeronautics and Space Administration's Lunar and Planetary Missions Board (LPMB), created in early 1967 under the chairmanship of John W. Findlay of the National Radio Astronomy Observatory, with Homer E. Newell, John E. Naugle, Donald P. Hearth, Oran Nicks, and Robert Kraemer as the principal NASA participants. The minutes of the LPMB over the period 1967-70 reflect intensive and comprehensive consideration of every subsequently conducted lunar and planetary mission, as well as several that have not yet been conducted.

I was deeply involved in these considerations as a member of both the SSB and the LPMB and adopted as my special function the advocacy of missions to the outer gaseous planets – Jupiter, Saturn, Uranus, and Neptune. In response to this advocacy, Findlay appointed a Jupiter Panel, later expanded to the Panel on the Outer Planets, consisting of Von R. Eshleman, Thomas Gold, Donald Hunten, Guido Münch, James Warwick, Rupert Wildt, and myself, as chairman. One of the early documents of this panel reads in part as follows:

> From the standpoint of basic physical phenomena, Jupiter is perhaps the most interesting of the planets. On the basis of radio evidence, it has an immense radiation belt of relativistic electrons and a magnetic moment perhaps as great as 10^5 times that of the Earth. As a planetary object it is in a decidedly different class than are the Earth, Venus, Mars, and Mercury. Consequently in situ measurements in the vicinity of Jupiter should be made an early objective of the national planetary program.

To our great pleasure, NASA issued an invitation to the scientific community on June 10, 1968, for proposals for scientific investigations on planned Asteroid/Jupiter missions. The stated areas of interest were as follows:

1. Interplanetary magnetic and electric fields and interplanetary particles of solar and galactic origin out to large heliocentric radial distances.
2. Particulate matter in and beyond the asteroid belt.

3. Particle and electromagnetic environment of the planet Jupiter.
4. Chemical and physical nature of the atmosphere of Jupiter and the dynamics thereof.
5. Thermal balance, composition, internal structure, and evolutionary history of Jupiter and its satellites.

This invitation elicited some 75 proposals by the December 2, 1968, deadline. Of these, 25 were ranked category 1 by the review committee. In early 1969, 11 instruments and 2 other investigations were selected, the missions were approved, and work got underway under the management of Charles F. Hall of the Ames Research Center of NASA. The two resulting missions – Pioneer 10, launched on March 3, 1972, and Pioneer 11, launched on April 6, 1973 – have been successful far beyond the expectations of their planners or even the participants. They have truly pioneered in making physical measurements in the outer solar system. Both spacecraft have successfully flown by Jupiter and have provided a greatly expanded knowledge of this planet and its satellites; Pioneer 11 continued onward to make the first exploration of Saturn in September 1979; and Pioneer 10, as of June 1982, is over 27 AU from the Sun. Both spacecraft continue to make unique observations of interplanetary phenomena at enormous heliocentric distances.

Parallel with the Pioneer 10/11 program, plans for follow-on missions to the outer planets were being formulated within the LPMB and elsewhere. One plan, called the Grand Tour of the Outer Planets, contemplated taking advantage of the uncommon configuration of Jupiter, Saturn, Uranus, and Neptune in the late 1970s and the 1980s by having a single spacecraft fly by all four of these planets. Although the Grand Tour as such was never approved, the plan was revived as a Jet Propulsion Laboratory program under the more modest title Mariner/Jupiter Saturn (MJS). I had the privilege of serving as chairman of the Science Working Group that developed the scientific rationale and general mission plan for MJS. The two spacecraft that emerged from these plans were, in due course, renamed Voyager 1 and Voyager 2, launched on September 5 and August 20, 1977, respectively.

By late 1981, each of the two Voyagers had flown through both the Jovian and Saturnian systems and had added a wealth of new knowledge of the physical properties of the planets themselves and their many satellites and rings. Voyager 2 is now targeted toward flybys of Uranus in January 1986 and Neptune in August 1989, thereby prospectively fulfilling the objectives of the Grand Tour, even though that term long ago became unmentionable in official circles.

The contents of this volume give ample testimony to the immense scientific achievements of these four outer planet missions. Each one of the hundreds, or perhaps thousands, of participants is entitled to an everlasting glow of pride in having had some part in their success.

James A. Van Allen

PREFACE

Why Jupiter? Is a book devoted solely to the magnetosphere of Jupiter too narrow, too specialized? With the present emphasis on solar-terrestrial relationships, why should we be studying other magnetospheres, and why Jupiter's? The primary reason is that Jupiter's magnetosphere is so unlike the Earth's in its fundamental workings. We study the Jovian magnetosphere because it is different. The difference challenges our understanding of magnetospheric physics. It leads us to a broader and more basic insight regarding both magnetospheric physics and the behavior of matter on a cosmic scale.

Jupiter is not an ordinary planet, nor does it have an ordinary magnetosphere. Although Jupiter's magnetosphere does most of the things Earth's does, it does them differently. For example, the Earth's magnetosphere extracts essentially all of its energy and some significant fraction of its plasma from the solar wind. In contrast, Jupiter's magnetosphere is powered by the slowing of Jupiter's spin, and nearly all of the magnetospheric plasma comes from internal sources – the satellite Io and the Jovian ionosphere. Jupiter also exhibits weak but genuine pulsar behavior. If we did not have the Earth's magnetosphere as a model, most theoretical work on the Jovian magnetosphere would probably be directed toward pulsar-type models.

The brief encounters of the two Pioneer and the two Voyager spacecraft with Jupiter have opened new frontiers of research in magnetospheric physics. Jupiter offers more than just another magnetosphere; it functions in a different mode and allows us to stretch our conceptions and develop better theories of the Earth's magnetosphere. The exciting promise of Jupiter's magnetosphere, lying within our solar system and accessible to us for direct measurement, is that it is also a link to distant astrophysical objects. The magnetosphere of Jupiter is wondrously complex; it seems to make room for nearly every idea that is proposed. Through in situ and ground-based measurements, we are developing a solid basis for extrapolation of space plasma physics to astrophysical objects. Such objects are so distant that all our information about them comes from various forms of remote sensing. Although some of our pre-Pioneer and pre-Voyager interpretations of ground-based (*i.e.*, remote-sensing) data from Jupiter were correct (for example, synchrotron emission from a planetary magnetosphere as a source of decimetric radio emissions), the interpretations of other data were far off-track. This has shaken the confidence of many in our ability to understand the basic workings of a large, complex system by relying solely on information obtained by remote-sensing techniques. For Jupiter, the problem is alleviated because our interpretation of the remote-sensing data can now be guided by the results of the four planetary flybys.

The primary goal of this book is to provide a concise, authoritative distillation of the body of literature on Jupiter published thus far. Most of the original literature is easily accessible, but, as one would expect, there is a lot of it. One unusual feature is its distribution. Although many relevant papers are widely scattered, much of the work is concentrated in a few special issues of the leading journals. Specifically, the results of the four flybys and some attendant theory are described in special issues of *Science* (Vol. 183, No. 4122, 1974; Vol. 188, No. 4187, 1975; Vol. 204, No. 4396, 1979; Vol. 206, No. 4421, 1979) and the *Journal of Geophysical Research* (Vol. 79, No. 25, 1974; Vol. 81, No. 19, 1976; Vol. 86, No. A10, 1981). There are also special issues of *Nature* (Vol. 280, No. 5725, 1979), *Icarus* (Vol. 27, No. 3, 1976; Vol. 44, No. 2, 1980), and *Geophysical Research Letters* (Vol. 7, No. 1, 1980). A book, *Jupiter* (edited by T. Gehrels, 1976), has been published that contains extensive discussions of pre-Voyager observations and theories. Finally, *The Satellites of Jupiter* (edited by David Morrison and published by the University of Arizona Press, 1982) is scheduled to appear contemporaneously with this book. Morrison's book should be considered a companion volume. It contains chapters that cover topics of direct interest to Jovian magnetospheric physics, such as Io's surface, volcanic emissions, atmosphere, and plasma torus. These topics are treated either in more detail or from a different viewpoint than the coverage in this book.

The task of providing an authoritative distillation of the literature on the Jovian magnetosphere is met by having a relatively small number of chapters written by authors who are, for the most part, willing to represent – or at least acknowledge the existence of – the work of distant colleagues. This book is an outgrowth of a meeting on Jovian magnetospheric physics held at Rice University in February 1980. The authors were invited, largely from among those who attended the meeting, on the basis of their expertise, breadth of interest, and writing ability. There were frequent communications among the authors to eliminate extensive duplication and to ensure that no significant topic would be inadequately covered. The result is a tightly interwoven book. The first eight chapters are largely descriptions of the experimental results and interpretations and conclusions derived therefrom. The final four chapters are devoted to the associated theoretical developments. Each chapter is reasonably self-contained, and they need not be read in any particular order. We suggest, however, that experimental results (first eight chapters) be read in conjunction with the appropriate theory (final four chapters). For example, Chapter 3, "The Low-Energy Plasma in the Jovian Magnetosphere," is closely tied to the theoretical developments in Chapter 11, "Plasma Distribution and Flow"; and Chapter 7, "Phenomenology of Magnetospheric Radio Emissions," should be read in conjunction with Chapter 9, "Theories of Radio Emissions and Plasma Waves." In some cases the reader may find it easier to read the theoretical chapter first. We definitely recommend some initial browsing.

Another goal is to make this book convenient for the reader and useful as a reference handbook. This is accomplished, in part, by the agreement in advance by the authors on a uniform system of symbol usage. Although there are stylistic differences from chapter to chapter, a degree of uniformity has been achieved. The principal symbols and acronyms used in this book, along with some brief definitions, are given in Appendix A; the coordinate systems used in the book are described in Appendix B, and a table of parameters for Jupiter and Io are in Appendix C. A list of tables follows the table of contents.

One of the delights in reading a book to which nearly two dozen authors have contributed is a revealing diversity of views and emphases. Jupiter's magnetosphere is complicated, and our understanding of its workings is primitive. Thus it should not be surprising, and certainly not alarming, to find some disagreement among chapters. Rather, such divergence is characteristic of an exciting field of research. There is much left to be done. If we are to understand Jupiter's magnetosphere and be able to generalize this understanding so that it can be applied to magnetized-plasma systems elsewhere in the universe, we must first argue among ourselves. Science knows no other way. The alert reader will spot such disagreement and might well use it as a basis for choosing a future research topic.

We are indebted to many for the production of this book: in particular, at Rice University, Dianne Drda†, editorial assistant, who organized and coordinated much of the diverse activity required to produce this work; Lorraine Dessler, who took over the task of editorial assistant during the final phases of coordinating and assembling this book; Georgette Burgess, who compiled the symbol and acronym list; and Jerry Mays, the best word processor operator I know. Tom Hill was a source of much good advice. The (relatively) low price of this book was made possible because of financial support from NASA Headquarters, specifically Robert Murphy and Henry Brinton of the Planetary Astronomy and Atmospheres Branch, and Erwin Schmerling and Michael Wiskerchen of the Upper Atmosphere and Magnetospheres Branch, who saw the value of this book and came to its aid while it was still in the conceptual stage. And finally, we wish to thank the staff of Composition Resources and of Cambridge University Press whose smooth professionalism solved many problems that might have otherwise become serious difficulties. The assistance of these people, of the anonymous referees, and of many others is implicit in this volume.

A. J. Dessler

† Dianne D. Drda (1943–1982)

During the past 17 years, most of the space physics community has had occasion, either directly or indirectly, to come in contact with Dianne Drda and her work. Starting late in 1965, she was copy editor for the Space Physics section of the *Journal of Geophysical Research.* She served as editorial assistant for *Reviews of Geophysics and Space Physics* from 1970 through 1974. At the time of her sudden and unexpected death from a cerebral aneurysm, she was working long hours on the production of this book. She worked with efficiency and with her typical cheerful demeanor both on this activity and as administrative secretary for the Department of Space Physics and Astronomy. The completion of this book, which she regarded with enthusiasm as a major reference work on Jovian magnetospheric physics, was important to her; she came within weeks of seeing it "in press."

As copy editor and as editorial assistant, she helped the community of space physicists in many ways. Her hallmarks were efficient professionalism in her craft and an infectious cheerfulness that brightened the day of those who talked with her. We shall miss her.