CONTENTS

List of tables viii
List of contributors ix
Foreword xi
Preface xiii

1. Jupiter's magnetic field and magnetosphere 1
   Mario H. Acuña, Kenneth W. Behannon, and
   J. E. P. Connerney
   1.1. Introduction 1
   1.2. The inner magnetosphere 2
   1.3. The middle magnetosphere 17
   1.4. The outer magnetosphere 31
   1.5. Summary 48

2. Ionosphere 51
   Darrell F. Strobel and Sushil K. Atreya
   2.1. Introduction 51
   2.2. Basic principles 51
   2.3. Ionization sources 52
   2.4. Ion recombination 55
   2.5. Ion chemistry 56
   2.6. Observations of Jupiter's ionosphere 58
   2.7. Structure of Jupiter's upper atmosphere 61
   2.8. Ionospheric modeling 63
   2.9. Concluding remarks 66

3. The low-energy plasma in the Jovian magnetosphere 68
   J. W. Belcher
   3.1. Introduction 68
   3.2. The Io plasma torus 69
   3.3. The Io flux tube 84
   3.4. The middle magnetosphere 86
   3.5. The outer magnetosphere 102
   3.6. Discussion 102

4. Low-energy particle population 106
   S. M. Krimigis and E. C. Roelof
   4.1. Introduction 106
   4.2. Observational overview 107
   4.3. Measurement of hot multispecies convected plasmas using energetic particle detectors 117
4.4. Presentation of results
4.5. Recapitulation and open questions
5. High-energy particles
   A. W. Schardt and C. K. Goertz
   5.1. Introduction
   5.2. Inner magnetosphere ($R < 15R_\star$)
   5.3. The subsolar hemisphere
   5.4. Predawn magnetosphere
   5.5. Jovian cosmic rays
   5.6. Summary and discussion
6. Spectroscopic studies of the Io torus
   Robert A. Brown, Carl B. Pilcher, and Darrell F. Strobel
   6.1. Introduction
   6.2. Observational basis: apparent emission rates
   6.3. The atomic clouds
   6.4. The plasma torus
   6.5. Radial transport
   6.6. Ionization and recombination
   6.7. Concluding remarks
7. Phenomenology of magnetospheric radio emissions
   T. D. Carr, M. D. Desch, and J. K. Alexander
   7.1. Introduction
   7.2. The decimeter wavelength emission
   7.3. The decimeter and hectometer wavelength emission
   7.4. Emissions at kilometric wavelengths
   7.5. Concluding remarks
8. Plasma waves in the Jovian magnetosphere
   D. A. Gurnett and F. L. Scarf
   8.1. Introduction
   8.2. Upstream waves and bow shock
   8.3. Trapped continuum radiation
   8.4. Upper hybrid and electron cyclotron waves
   8.5. Whistler-mode waves
   8.6. Broadband electrostatic noise
   8.7. Discussion
9. Theories of radio emissions and plasma waves
   Melvyn L. Goldstein and C. K. Goertz
   9.1. Introduction
   9.2. Linear theories
   9.3. Nonlinear theories
   9.4. The Io and plasma torus interaction
   9.5. Summary
10. Magnetospheric models
    T. W. Hill, A. J. Dessler, and C. K. Goertz
    10.1. Introduction

11. Plasma distribution and flow
    Vytenis M. Vasylunas
    11.1. Introduction
    11.2. Plasma configuration in the middle and outer magnetosphere
    11.3. Models of the magnetic field and stress balance
    11.4. Plasma flow models
    11.5. Conclusion
12. Microscopic plasma processes in the Jovian magnetosphere
    Richard Mansergh Thorne
    12.1. Introduction
    12.2. Wave-particle interactions in the terrestrial magnetosphere
    12.3. Plasma instability and quasilinear scattering in the Jovian magnetosphere
    12.4. Precipitation fluxes and the Jovian aurora
    12.5. Energy transfer processes

Appendix A. Symbols and acronyms
Appendix B. Coordinate systems
Appendix C. Jupiter and Io: selected physical parameters
References
Index
### TABLES

1.1. Spherical harmonic coefficients for magnetic field models  page 4
1.2. Characteristics of dipole terms for magnetic field models  5
1.3. Characteristics of offset tilted dipole (OTD) magnetic field models  7
1.4. Summary of Voyager boundary crossings  44
2.1. Important reactions in the ionosphere of Jupiter  57
3.1. Composition of the plasma in the dayside magnetosphere of Jupiter  80
3.2. Vector velocities in the cold torus as seen in the corotating frame  83
5.1. Energetic particle detectors  160
6.1. Observed emitting species in the Io torus  198
6.2. Io torus electron density measurements  204
6.3. Io torus electron temperature measurements  205
6.4. Charge-exchange reactions  209
6.5. Thermally averaged collision strengths  215
6.6. Io torus number density  216
7.1. Historical milestones in Jupiter radio astronomy  229
7.2. Components of Jupiter’s radio spectrum  230
7.3. Fourier amplitudes and phases of polarization position angle as a function of CML; measurements at about 2700 MHz during October 1975  244
7.4. Components of Jupiter’s decametric emissions  255
8.1. Plasma wave modes  286
8.2. Jovian plasma waves  314
9.1. Summary of direct linear mechanisms  329
10.1. Injection of ions  359
10.2. Energy budget  362
10.3. Jupiter’s pulsar behavior  378
10.4. Spin-periodic phenomena  381
11.1. Validity of thin-sheet approximations  403
11.2. Magnetotail parameters derived from magnetopause model  443
12.1. Wave-particle resonant interactions  461
12.2. Wave-particle energetics in the Jovian magnetosphere  485

### CONTRIBUTORS

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mario H. Acuña</td>
<td>Goddard Space Flight Center Greenbelt, MD 20771</td>
</tr>
<tr>
<td>J. K. Alexander</td>
<td>Goddard Space Flight Center Greenbelt, MD 20771</td>
</tr>
<tr>
<td>Sushil K. Atreya</td>
<td>Department of Atmospheric and Oceanic Science Space Research Building University of Michigan Ann Arbor, MI 48109</td>
</tr>
<tr>
<td>Kenneth W. Behannon</td>
<td>Code 692 Goddard Space Flight Center Greenbelt, MD 20771</td>
</tr>
<tr>
<td>J. W. Belcher</td>
<td>Massachusetts Institute of Technology Room 37-695 Cambridge, MA 02139</td>
</tr>
<tr>
<td>Robert A. Brown*</td>
<td>Lunar and Planetary Laboratory University of Arizona Tucson, AZ 85721</td>
</tr>
<tr>
<td>T. D. Carr</td>
<td>Department of Astronomy University of Florida Gainesville, FL 32611</td>
</tr>
<tr>
<td>J. E. P. Connerney</td>
<td>Goddard Space Flight Center Greenbelt, MD 20771</td>
</tr>
<tr>
<td>M. D. Desch</td>
<td>Code 695 Goddard Space Flight Center Greenbelt, MD 20771</td>
</tr>
<tr>
<td>A. J. Dessler†</td>
<td>Department of Space Physics and Astronomy Rice University Houston, TX 77251</td>
</tr>
<tr>
<td>C. K. Goertz</td>
<td>Department of Physics and Astronomy University of Iowa Iowa City, IA 52242</td>
</tr>
<tr>
<td>Melvyn L. Goldstein</td>
<td>Code 692 Goddard Space Flight Center Greenbelt, MD 20771</td>
</tr>
<tr>
<td>D. A. Gurnett</td>
<td>Department of Physics and Astronomy University of Iowa Iowa City, IA 52242</td>
</tr>
<tr>
<td>T. W. Hill</td>
<td>Department of Space Physics and Astronomy Rice University Houston, TX 77251</td>
</tr>
<tr>
<td>S. M. Krinigis</td>
<td>Applied Physics Laboratory Johns Hopkins University Laurel, MD 20707</td>
</tr>
<tr>
<td>Carl B. Pilcher</td>
<td>Institute for Astronomy 2680 Woodlawn Dr. Honolulu, HI 96822</td>
</tr>
</tbody>
</table>

* 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
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. Heath, 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 subsequenty 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 Hunt, Guido Münch, James Warwick, Rupert Wüst, 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 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.
Foreword

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 under- way under the direction and 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 flyby 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 emission), 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,
Preface

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 Deslser, 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 Wiescher 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.