Space Plasma Physics:

The Study of Solar-System Plasmas

Volume 1
Reports of the Study Committee and Advocacy Panels

The National Research Council

Space Science Board

Assembly of Mathematical and Physical Sciences

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Foreword

The space age began exactly 20 years ago with the launch of Sputnik I and Explorer I. The Explorer spacecraft discovered regions of trapped radiation around the earty—the van Allen belts. This was the beginning of the study of particles and fields in space, or space plasma physics. A large part of the effort in the early years of the space program was devoted to the mapping of the magnetosphere, the measurements of time variations in particles and fields, and the exploration of the solar wind.

From these studies a sophisticated empirical knowledge of phenomena in space plasma physics has emerged. With the attainment of this observational maturity in the field, NASA funding for space plasma physics has declined as priorities have shifted to other exploratory ventures. The present study of space plasma physics was therefore requested by NASA in order to obtain guidance for future directions in the subject.

The study has involved a major effort on the part of a great many people working in space plasma physics. The Space Science Board formed a panel chaired by Stirling Colgate, composed for the most part of physicists expert in plasma physics but not especially knowledgeable about the space aspects of plasmas; the report of this panel constitutes the first part of Volume 1 of the report. The Committee on Space Physics of the Board was charged with the responsibility for soliciting technical review papers on a large number of topics in space plasma physics. These reviews are to be printed in Volume 2 of the report; they constitute a most valuable resource for those working in the field. From these reviews, two advocacy panels prepared overview position papers that served as resource information for the Colgate panel and appear as Chapters 7 and 8 of this report.

The Colgate panel has recommended that future research in space plasma physics should involve a much closer integration between theory and observation as is appropriate to the maturity of the field and in order to bring the research into closer contact with the mainstream of plasma physics research. The panel also concurred in the unified recommendations of the advocacy panels. The Space Science Board has thoroughly reviewed all the material that appears in Volume 1, and it has adopted the guidelines that appear herein as its own policy.

The Space Science Board is most grateful to the many people who have devoted so much time and effort to carrying out this study.

A. G. W. Cameron, *Chairman*
Space Science Board

Preface

This study was undertaken by a specially created committee of the Space Science Board of the National Research Council, at the request of the National Aeronautics and Space Administration, in order to identify the future objectives of research in space plasma physics.*

The committee included six members who are familiar with the broad aspects of plasma physics but not specifically solar-system plasmas and three members with special interests in space plasmas. These last three members also chaired panels composed of advocates of specific subdisciplines of space plasma physics. The overviews of these panels appear as Chapters 7 and 8. The individual scientific review papers generated by these panels, which served as the scientific basis for the study, are contained in Volume 2 of this report.

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*Plasma is matter in the ionized state. Space plasma physics concerns the study of plasmas in the space environment. A major fraction of both astrophysical and controlled thermonuclear fusion research depends on both an abstract and experimental understanding of plasmas, plasma interaction, the behavior of plasmas in electromagnetic fields, and the acceleration of charged particles.

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Report of the Study Commit

1

Principal Conclusions

1. (a) Space plasma physics is intrinsically an important branch of science. The intellectual significance of the study of solar-system plasmas is documented by its contributions to the development of general plasma physics and by its role in illuminating astrophysical phenomena both internal and external to our solar system.

(b) On the directly practical side, a better understanding of solar-system plasmas might have substantial importance for terrestrial communications and meteorology.

2. Now that the initial exploratory stage of space plasma physics has been completed successfully, the fruitfulness of future projects will depend on addressing basic scientific problems. The solution to these problems will call for a logical cycle of theoretical problems definition, the planning of experiments and hence missions, data collection, data reduction, and theoretical analysis, leading to a progressive refinement of the science.

3. The theoretical component of the space-plasma-physics effort needs to be strengthened by increased support and, most particularly, by encouraging theory to play a central role in the planned development of the field.

4. We agree with the unified recommendations of the advocacy panels.

2
Introduction

The part of our universe that is accessible to direct experimental contact or close observation has been extended by chemical reaction vehicles to include much of the solar system. Except within and at the interface with planets, the vast extent of space is filled with ionized matter called plasma. Man's ventures into space take place in this plasma environment. For these reasons, plasma studies have been of major concern to the National Aeronautics and Space Administration (NASA). The discovery of extraordinarily diverse conditions in solar-system space plasmas has been exciting in its own right. Since the solar system is presumably a microcosm of interstellar, galactic, and extragalactic space, these discoveries have considerable implications for wider astrophysical problems. Solar-system plasmas have the unique and useful feature that they can be observed closely and in many cases probed internally with local or *in situ* detectors, whereas the rest of the astrophysical environment will likely remain remote. Solar-system plasmas are not only a part of the astrophysical environment but also provide an extension of conditions available in laboratory plasmas.

2.1 MOTIVATIONS FOR RESEARCH

The motivations for pursuing the study of solar-system plasma physics fall into three categories:

(a) As an adventure, "because it is there"—the desire to know the environment in which we live.

(b) As an important branch of science, concerned with problems of true intellectual significance that may be studied effectively in space and whose importance extends to laboratory physics as well as to large-scale astrophysics.

(c) As a potential source of applications, e.g., prediction of magnetic storms and perhaps even of climatological variations.

The initial impetus for space-science research has properly been given by category (a); its eventual importance may well lie more in category (c). However, it is the judgment of this panel that the nature of the space-science research program should be governed by an explicit recognition that at this time the driving motivation should be predominantly category (b). Thus, in order to promote deeper understanding of phenomena already observed, we believe that experiments should be motivated more closely by well-posed theoretical questions than has been the case heretofore. This implies a stronger commitment to computational effort in the support of theoretical models and an attempt at closer integration with laboratory plasma physics.

2.2 THE PROBLEMS

We have identified six general abstract problems, vital to further understanding of space plasmas, that have already received considerable theoretical attention and have important implications beyond the study of solar-system plasmas. These are: (1) magnetic-field reconnection, (2) the interaction of turbulence with magnetic fields, (3) the behavior of large-scale flows of plasma and their interaction with each other and with magnetic and gravitational fields, (4) acceleration of energetic particles, (5) particle confinement and transport, and (6) collisionless shocks.

Of these problems perhaps the only one that has hitherto been addressed by the space research program in a reasonably systematic way is the last, and it is precisely the collisionless shock problem on which space science has had the greatest impact. The other topics, especially (1) and (5), are clearly of key importance to controlled fusion research, while all six are of considerable astrophysical interest.

2.3 MAGNETIC-FIELD RECONNECTION

While our understanding of all six of the above basic problems should be closely tied to future space-physics experiments, we shall consider as an example only the first: magnetic-field reconnection.

Under a wide variety of conditions, plasma tends to be frozen to magnetic-field lines. Such "freezing" is, however, not perfect; if it were, then perfect plasma confinement would be possible in the laboratory, matter would be less likely to escape from evolving stellar systems, and convection would not occur in magnetized stars. Quite generally, the constraint breaks down locally in the vicinity of so-called neutral sheets, where the direction of magnetic-field lines reverses. In the vicinity of these singular regions, there can arise so-called "tearing instabilities," in which the constraining fields are reconnected at a rapid rate. This magnetic-field reconnection may occur gradually or explosively. When it occurs explosively, it can lead to auroral substorms and solar flares or to disruptions of the discharge channel in laboratory experiments with tokamaks*; when it occurs gradually in interstellar space, stellar convective layers, or stellar surfaces, the result is a quasi-static but greatly enhanced dissipation of magnetic energy and rearrangement of the field topology.

The "tearing mode" description was first introduced to explain the resistive instabilities of various high-current laboratory plasma experiments. These ranged from the case of currents perpendicular to the magnetic field with maximum particle pressure at the neutral sheet (a case known in its space-plasma manifestation as "neutral sheet annihilation") to the opposite extreme of sheared magnetic fields and parallel currents, with the pressure everywhere zero (a case known as "field-aligned currents" in the context of space plasmas).

Theories of the linear tearing mode exist: the stability computations are straightforward but depend in a complex way on the details of the situation. Considerable progress has recently been made on the computational study of the nonlinear resistive tearing mode in connection with tokamak research; corresponding progress could be made on a computational study of collisionless tearing modes applied to solar-system phenomena such as those seen in the earth's magneto tail or flow-driven modes like those at the magnetopause.

On the basis of such theoretical studies, new experiments in space could be designed that might

(a) Locate the existence of the neutral layer by monitoring distant effects (waves, field changes, particle streams), so that data could be accumulated more efficiently in the region of maximum interest;

(b) Utilize the knowledge of the theoretical time and distance scales of the phenomenon to design the data system;

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*A tokamak is a magnetic containment device for plasmas used in controlled thermonuclear fusion research.

(c) Measure quantities of theoretical interest, such as normal magnetic-field components, local electric fields, and accelerated particles; and

(d) Use active means for triggering the instability since the neutral layer is in a metastable state.

By combining theory with experiment, one would thus learn both more about magnetic-field reconnection *per se* and about its importance for a variety of solar-system and astrophysical processes.

We have pointed out six basic scientific problems—important to technology and to the comprehension of the universe—to which valuable contributions can be made by space science. We have discussed one of these topics; similar discussions could be given of the other five. The resolution of these problems would not only make a general scientific contribution but also would facilitate the detailed quantitative understanding of the solar-system plasma, the magnetics of the sun, and, by inference, the behavior of more general astrophysical plasmas.

3
Application

3.1 PLASMA ASTROPHYSICS

The opening of new observational "windows" in astronomy over the past few decades, involving radio waves, x rays, gamma rays, and cosmic rays, has revolutionized astronomy and astrophysics and revealed the existence of a broad range of previously unsuspected phenomena. Because plasma physics is basic to the understanding of many of these new phenomena, their study may properly be labeled plasma astrophysics.

Thus, gamma rays are produced in the interactions of galactic cosmic rays (which are properly regarded as a part of the interstellar plasma) with ambient gases. Most, if not all, compact x-ray sources are binary systems in which plasma is accreted by a compact star (a neutron star, black hole, or degenerate dwarf) from a more massive stellar companion. The structure and evolution of the gaseous part of a galaxy is controlled to a large extent by hydromagnetic and plasma-dynamical processes. Understanding of the bewildering variety of extra-solar-system radio sources, including quasi-stellar objects, head-tail sources, pulsars, and the interstellar medium, will most certainly involve plasma physics as an essential ingredient. The new astrophysics gives real significance to the statement that more than 99 percent of the matter in the universe is in the plasma state.

It is, therefore, clear that modern astrophysics rests to a large degree on our basic understanding of plasma physics. Experience with both laboratory and solar-system plasmas, which can be probed directly, provides valuable insight into general problems of plasma physics and allows theories to be carefully compared with observations. Without the constraints imposed by direct observation, our theories of astrophysical phenomena would be much more speculative.

The range of parameters found in astrophysics is, of course, considerably different from that of laboratory plasmas, and the interpretation of laboratory plasma phenomena can be affected seriously by the closeness of boundaries. On the other hand, the plasmas in the solar system are examples of semi-infinite astrophysical plasmas. The boundary conditions are more relevant to astrophysics, and the parameter ranges are closer to those occurring in astrophysics. For this reason, solar-system plasmas provide a relatively convenient, accessible "laboratory" where many of the phenomena seen in astrophysics can be closely observed. The impact of this science on astrophysics has been significant and should be more so in the future.

As one specific example of the applicability of solar-system plasma physics, consider the case of cosmic-ray transport. A general theory of cosmic-ray transport has been developed, primarily in response to observations of cosmic rays in the solar system. This theory relates the transport coefficients to directly observable properties of the ambient plasma. The direct comparison of observations of both solar and galactic cosmic rays with simultaneous, direct plasma observations is providing a stringent test of the theory. These general transport theories are applicable to cosmic rays elsewhere in the universe, and they can be used with greater confidence and understanding because of the tests carried out in the solar system.

Cosmic-ray transport is but one of many examples that illustrate the relationship between solar-system plasmas and astrophysics and that document the importance of solar-system plasma physics in constraining and shaping our interpretation of more-distant astrophysical phenomena.

3.2 PLASMA EXPERIMENTS IN SPACE AND IN THE LABORATORY

Space and laboratory experiments are complementary. They explore different ranges of dimensionless physical parameters. Space plasma configurations usually contain a much larger number of gyroradii and Coloumb mean free paths than achieved in laboratory plasma configurations. In the laboratory, special plasma configurations are set up intentionally, whereas space plasmas assume spontaneous forms that are recognized only as a result of many single-point measurements. Space plasmas are free of boundary effects; laboratory plasmas are not, and often suffer severely from surface contamination. Because of the differences in scale, probing a laboratory plasma disturbs it; diagnosing a space plasma usually does not. The pursuit of static equilibria is central to high-temperature laboratory plasma physics, whereas space plasma physics is concerned with large-scale time-dependent flows.

Many of the fundamental problems listed above have been addressed both in space and in the laboratory.

Collisionless shocks were first detected in space, and the parametric dependence of shock structure was delineated in space. Particular shock structures have also been investigated in the laboratory. Understanding of the turbulent loss of trapped particles from fusion mirror devices and the earth's radiation belts was achieved at virtually the same time. The scattering of electromagnetic radiation from turbulent laser fusion and from ionospheric plasmas were pursued in parallel. We foresee a similar fruitful interaction between space and laboratory on the topics of magnetic reconnection and turbulent beam–plasma interactions. In tokamaks, reconnection phenomena similar to those of the heliosphere determine the gross stability of the plasma and affect microscopic transport as well. Large quiescent magnetized plasma devices have recently been developed in the laboratory, and studies of beam–plasma interactions therein are yielding results useful to space plasma—and particularly auroral—physics.

Certain problems are best studied in space: large-scale turbulent hydromagnetic flows and acceleration and transport of relativistic ions are examples. Certain problems could be more conveniently addressed in the laboratory, e.g., parametric studies of the effects of geometry and plasma properties on reconnection. Theory should make the results of either laboratory or space experiments available for the benefit of the whole field of plasma physics.

3.3 RELEVANCE OF SOLAR-SYSTEM PLASMA PHYSICS TO TECHNOLOGY AND SOCIETY

In the past, ionospheric–magnetospheric research has been primarily motivated by the desire to understand natural phenomena in order to optimize the performance of technological systems. An obvious example is terrestrial radio propagation via ionospheric reflection. Although ionospheric processes are still far from completely understood, predictive techniques developed over the years have made it possible to anticipate propagation blackouts and anomalies reasonably well. While the use of satellite transmissions at higher frequencies (gigahertz range) has eliminated the need to worry about ionospheric

reflection effects on radio signals for many applications, ionosphere-produced scintillations of satellite communication signals have recently been found to cause transmission anomalies. Further, the plasma environment of the communication satellites is often unpredictable and hostile rather than benign as was tacitly assumed when such satellites were first proposed by Arthur Clarke and John Pierce.

Currents flowing in the earth's ionosphere have so far been used for deep ground-based induction studies of the earth's crust and upper mantle. However, the spatial distributions and nonuniformities of these currents, as well as their temporal behavior, need to be better understood to make the method generally applicable. Moreover, while useful to the induction geophysicist, such currents form an unwanted background for the petroleum and mineral prospector, particularly at high latitudes near the auroral zones, and produce as well a time- and space-varying background that cannot readily be eliminated for low-altitude magnetic-survey spacecraft.

As the technological use of space increases, other ways in which space plasma influences contemporary technology will likely be discovered. For example, it has been suggested that solar-system plasma disturbance transmitted through the magnetosphere and ionosphere can affect earth's weather on both long-term and short-term bases. Conversely, we may find that man is affecting the magnetosphere and ionosphere via his activities; for example, does (or will) the electromagnetic radiation in the magnetosphere from the North American and European power grids affect the magnetosphere and ionosphere in ways that could become deleterious to various technologies? Deeper understanding of the plasma processes in the solar system will enable us both to anticipate possible impacts of the system on new technologies as they develop and to continue to examine the extent to which expanding human activities might adversely affect the system itself.

4
Implementation

Exploration and monitoring of our solar-system space environment must be closely tied to reliable theory for several reasons: (1) Even if a complete and detailed phenomenological description of solar-system plasmas were to be developed without a sophisticated theoretical model, we would not know how this space environment would respond to conceivable man-made perturbations or to natural ones such as future or past solar activity. (2) Theory must provide a precise definition of important parameters and regions for measurement programs in order to maximize the return of significant data from missions. (3) Only when reliably tested theoretical models become available can the results be used to develop models of other regions of our universe and to have an impact on the rest of astrophysics. The present role of theory in mission design and the ratio of theoretical to observational studies in space plasma physics is not appropriate to these tasks.

As the development of space plasma physics approaches the end of its second decade, the magnitude and role of the needed theoretical activity appears to be inadequate. In important ways this has always been the case, but an imbalance between large-scale uncritical data acquisition on the one hand and inadequate data reduction and theory on the other has increasingly serious consequences as a science matures. Early exploratory missions that gave a first look at new physical regions brought relevant and exciting information even without the guidance of optimal, or even adequate, theoretical models in their design. As the rough outline of the structure of the solar-system plasmas has become clearer, there is good reason to expect surprises and excitement from future missions only if the mission objectives and analysis are carried out with proper theoretical underpinnings. To be significant, missions will have to measure

important parameters of sophisticated theories that are much more than phenomenological descriptions.

Too often, theoretical work is carried on mainly by a "house theorist," attached to an experimental program, who has neither an independent voice nor support. Numerical simulation and modeling studies have lagged. Complete data reduction has suffered from lack of funds despite what should have been its very high priority in any mission.

Elementary-particle physics, a much more mature subject, has many of the problems of space plasma physics: very few, very expensive national facilities for which many user groups propose experiments and a great variety of possible measurement programs. The high-energy physics community has developed a style for the advancement of the field which the space-plasma-physics program might emulate. The main theme in the support of high-energy physics is that a continuing confrontation between experiment and theory is necessary not only for the health of both but to achieve a real understanding of nature. The latter must not be weaker than the former. In program committees, which decide the allocation of time and resources at the accelerators, theorists play at least as important a role as experimenters. Theory has its own support, which enables theorists to exist in independent groups within which there are critical and fruitful interactions. Thus, there is a permanent strong group of scientists who contribute ideas, suggest experiments, and enthusiastically study data from experiments as they become available. They remain vigorous even in the intervals between major experimental discoveries. Much more of this is achieved by National Science Foundation or Department of Energy support of theoretical academic research at universities than at the national laboratories where the experimental work is done.

It should be noted that a different successful pattern of theoretical effort has developed in the field of controlled thermonuclear research. Here the bulk of theory has been done by groups within the national fusion laboratories. These groups have historically always been strongly supported and have played an integral role in the basic decision making. At least two of these laboratories have close connections with major universities, and many of the theorists are involved with the educational programs.

We would hope that greater federal support would be directed toward the development of theoretical groups that play a role in space-plasma physics similar to that which such groups play in high-energy physics. This would involve vigorous continuing support even in intervals between missions, with a goal of developing optimal models of solar-system plasmas that may ultimately have application also to plasmas elsewhere in the universe and in the laboratory. The present theoretical support is not sufficient to do this.

It is important to develop a community of scientists who have a comprehensive view of the field, that is, who are able to put problems in a theoretical perspective in which the relationships between studies of magnetospheres, plasma instabilities, and turbulence, for example, in widely different physical environments are appreciated and emphasized, as is the relationship of such studies to work on other aspects of statistical physics and hydrodynamics. The future development of space-plasma physics requires a combination of excellent experiments and excellent theory.

The scientific problems and their analytical understanding should serve as a focus for the future space-plasma-physics research program. The endeavor to understand the plasma phenomena of the solar system can best succeed if it is undertaken as a systematic scientific investigation rather than as an afterthought to space exploration.

II

Panel Overviews

5

Introduction

Plasma physics is the study of partially or fully ionized electrically conducting gases. It is currently among the most advanced disciplines of classical physics, drawing its methodology from such diverse fields as statistical mechanics, classical electricity and magnetism, hydrodynamics, and atomic physics. Plasma physics currently has important technological applications to energy, the environment, and space technology, among others.

The broad discipline of plasma physics may be further subdivided into three main areas: laboratory plasma physics, plasma astrophysics, and solar-system plasma physics. Solar-system plasma physics is the study of plasma phenomena throughout the solar system, extending from the solar photosphere to the outer boundary of the heliosphere. The heliosphere is the cavity formed into the interstellar medium by the solar wind. The solar wind is a nearly fully ionized magnetized supersonic and super-Alfvénic plasma flow generated in the solar corona. It flows radially outward from the solar system until it is terminated by its interaction with the interstellar medium. The solar wind interacts uniquely and significantly with, at least, several of the planets in the solar system. When a planet has a sufficiently strong intrinsic magnetic field, this interaction forms a magnetosphere. Either the solar-wind-created magnetosphere or the solar wind itself interacts with comets, asteroids, and cosmic rays. All of these phenomena, together with those occurring on the surface of the sun and in the solar corona, such as solar flares, are included in solar-system plasma physics.

Because solar-system plasma physics takes place not in the laboratory but in the natural environment, purely plasma physical phenomena cannot always be neatly isolated. For this reason, solar-

This chapter was prepared by C. F. Kennel, L. J. Lanzerotti, and E. N. Parker.

system plasma physics has significant regions of overlap with other scientific disciplines, the most significant being with plasma and high-energy astrophysics. However, the primary, if not sole, disciplinary language used to describe the aforementioned phenomena is that of plasma physics. Thus, there is a fundamental and complementary relation between the study of plasmas in the laboratory and in the solar system.

It is convenient to separate the study of large-scale macroscopic and small-scale microscopic processes in plasmas. Magnetohydrodynamics (MHD)—magnetized plasma flows and equilibria—describes the plasma as a conducting fluid, a convenient simplification that enables the large-scale structure and dynamics of hydromagnetic objects to be described efficiently. Microscopic plasma physics—or alternatively kinetic theory of plasmas—treats the plasma as a collection of individual charged particles that collide infrequently and interact with self-consistent electric magnetic fields induced by the particles' motions. The relationship between kinetic theory and magnetohydrodynamics is very close. First, kinetic theory, being the more fundamental description, must be used to define the conditions of validity of MHD theory, which is simpler to use. Even more importantly, the transport processes—viscosity, electrical resistivity, and heat conduction—inserted into the hydromagnetic equations as coefficients cannot be evaluated to collision-free plasmas without considering the microscopic theory of turbulent plasmas. These transport processes are typically important in thin boundary layers—shock waves and magnetopauses are examples. Thus, the macroscopic description of hydromagnetic systems is incomplete without considering the dissipation due to microscopic plasma waves and turbulence.

The Space Science Board divided its study of plasmas in the solar system into four parts. The Study Committee on Space Plasma Physics, chaired by Stirling A. Colgate, consisted of six experts drawn from laboratory plasma physics and plasma astrophysics and the chairmen of three advocacy panels. Its function was to give an overall evaluation of the current status of solar-system plasma physics. The Study Committee on Space Plasma Physics was aided by three "advocacy" panels, whose members were practicing solar-system plasma physicists: a Panel on Plasma Physics of the Sun, chaired by E. N. Parker, a Panel on Solar System Magnetohydrodynamics, chaired by C. F. Kennel; and a Panel on Solar System Plasma Processes, chaired by L. J. Lanzerotti. The Kennel and Lanzerotti panels dealt with plasma phenomena beyond the solar corona. Solar-system magnetohydrodynamics treated large-scale plasma phenomena in the solar wind and at the planets. Solar-system plasma processes considered those microscopic plasma problems that emerged from the study of the objects considered in solar-system magnetohydrodynamics and also considered the impacts of these processes on terrestrial science and technology. The solar-physics panel treated macroscopic and microscopic plasma processes occurring on the sun together and included many topics from what is conventionally called solar astronomy.

Each member of the advocacy panels on solar-system magnetohydrodynamics and solar-system plasma processes wrote a scientific review article on his specialty. Using these review articles as working papers, these two advocacy panels met to compose overview reports that summarized the salient points of the working papers and made recommendations. The Committee on Space Physics of the Space Science Board (SSB), chaired by R. A. Helliwell, appointed outside reviewers for each of the scientific review articles and supervised the reviewing process. These working papers are to be published as Volume 2.

The brief overview report on the plasma physics of the sun was prepared by E. N. Parker to accompany the longer overviews on solar-system magnetohydrodynamics and solar-system plasma processes. It provides an updated introduction to the more detailed report on solar physics that appears as a working paper in the SSB's *Report on Space Science, 1975* (National Academy of Sciences, Washington, D.C., 1976). The scientific objectives outlined in the solar-physics report, but not the specific mission recommendations, are considered to be an integral part of the overview documents of the report of the study committee. They provided input for the general recommendations that accompany the overview reports.

The overview papers of the solar-system magnetohydrodynamics and plasma processes panels and a brief extract of the solar-physics report appear here as appendixes to the overall report of the Study Committee on Space Plasma Physics. These three overviews were reference documents for the Study Committee and were reviewed in detail by the Committee on Space Physics. In addition, R. A. Helliwell, C. F. Kennel, L. J. Lanzerotti, and E. N. Parker prepared a distillation of the recommendations of the three advocacy panels. These unified recommendations also appear here.

On May 27, 1977, the SSB accepted the report of the Study Committee on Space Plasma Physics as its assessment of the current status of solar-system plasma physics. Upon the recommendation of the Committee on Space Physics, the SSB accepted the reports of the three advocacy panels and its assessment of the current status of these three fields. The SSB adopted the recommendations of the Committee on Space Plasma Physics and the unified recommendations of the three advocacy panels as Board policy. Finally, the Board directed its Committee on Space Physics to generate by May 1978 a ten-year strategy for solar-system plasma physics based on the above assessment.

6

Unified Recommendations of the Advocacy Panels

These unified recommendations have emerged from a detailed examination of solar-system plasma physics by the Panels on Plasma Physics of the Sun, Solar System Magnetohydrodynamics, and Solar System Plasma Processes. They were distilled from the panel reports by the chairman of the Committee on Space Physics together with the chairmen of the above panels.

6.1 BASIS FOR RECOMMENDATIONS

1. Many important interactions between the principal parts of the solar system—the sun, interplanetary medium, and planets—are plasma physical in nature.
2. Studies of solar-system plasmas enlarge our total knowledge of plasma physics, which has important technological applications to energy, the environment, and space technology, among others.
3. A successful space plasma-physics research program must achieve an effective balance among space missions, theory, data analysis, and ground-based observations and experiments. In particular, theory will become an increasingly important factor in determining the success of future missions concerned with solar-system plasma physics.

6.2 RECOMMENDATIONS

1. We recommend that solar-system plasma physics should have high priority in order to remain an integral part of the space-science research effort of the United States.

2. We recognize and encourage the existing trend toward problem-oriented missions in solar-system plasma physics. We recommend that the specific scientific questions discussed in the overviews serve as a focus of an active problem-oriented missions program devoted to observation and interpretations of the plasmas on the sun, near the earth and other planets, and in the interplanetary medium.

In solar-system plasma physics, in particular, theory and data analysis play a crucial role in generating the objectives of new missions. This fact motivates the following recommendations:

3. We recommend that future mission planning and implementation be guided by the following considerations:

(a) The research program of solar-system plasma physics—including solar and solar-wind plasma physics and terrestrial and planetary magnetospheric and ionospheric physics—should be planned together.

(b) Since theory and new technology are rapidly evolving, planning and its implementation should be regularly updated by Space Science Board review of ongoing missions, theory, experiment, and new technology.

(c) Planning for future missions in space plasma physics should be based on assessments of priorities derived from considerations of potential scientific return in relation to mission costs.

4. To realize the benefits from space missions in solar-system plasma physics we recommend:

(a) Support for extended mission data analysis in cases of high scientific interest;

(b) Specific support for ground-based observations that complement the objectives of space missions;

(c) That the institution of guest investigators for detailed analyses and theoretical work on specific mission programs be continued and extended.

5. To realize the benefits from the nation's program in solar-system plasma physics, we recommend:

(a) Strengthening theoretical solar-system plasma physics and, to aid in achieving this goal, support for computer modeling;

(b) Stable support for data analysis and interpretation outside of missions;

(c) Support for ground-based observations and laboratory experiments that can increase understanding of space plasmas.

6. Since advances in neighboring fields now are important to the advance of solar-system plasma physics, we recommend that communication between the major plasma activities—laboratory, astrophysical, and solar-system plasma physics and solar astronomy—be strengthened by means such as interdisciplinary working groups and conferences.

7

Solar-System Magnetohydrodynamics

7.1 INTRODUCTION

The years 1957–1960 mark a watershed in scientific history. Two events symbolizing the deeper intellectual currents of those years were the first successful launch of an artificial earth satellite by the Soviet Union in 1957 and the revelation, through declassification, that both the United States and the Soviet Union had been trying to harness the energy source of the sun–thermonuclear fusion–for human purposes. Then as now, the obstacles to achieving controlled thermonuclear fusion lay not in our ignorance of nuclear physics but in our poor understanding of the physics of fully ionized gases–plasma physics. In 1958, the terrestrial radiation belts were discovered, and in 1960 the solar wind, both by spacecraft-borne instruments. These made it clear that our exploration and future understanding of the earth and sun's space environment would also be couched in terms of plasma physics–a discipline of classical physics that had lain relatively dormant until called forth by human need and curiosity. By 1960, the foundations of modern plasma physics had been constructed. In the future, it would develop in two separate but parallel directions, carried onward by a larger intellectual tide quite different from the one that had characterized physical science prior to World War II. Since the Second World War, the ultimate survival of the human race has been called into question. Controlled thermonuclear research is one response to this imperative, seeking, as it does, a source of energy accessible to human use that will last for a time comparable with the present age of the earth; space research is another, seeking as it does not abstract laws of physics but useful comprehension of nature's processes on a global and, indeed, solar-system scale, in recognition of man's intimate and sensitive dependence on his environment. It is both symbolically and substantially significant that the same discipline of physics–plasma physics–defines the basic language used both in controlled thermonuclear research and in solar-system plasma physics, a part of which is the subject of our discussion to follow.

Twenty years of space research have taken place since the watershed–almost a whole human generation. These 20 years have seen men walk on the moon, routine photography of the whole earth, a new writing of the history of the universe, the discoveries of neutron stars and possibly black holes, and many other things; in our own subject, solar-system plasma physics, they have seen the ancient problems of the *aurora polaris* and solar-terrestrial magnetic activity nearing resolution. They have taught us that the earth, and indeed most of the planets, have an atmosphere above the one we breathe, made of plasma–a magnetosphere. They have taught us that the sun's outermost plasma atmosphere is a wind blowing outward past all the planets of the solar system. And the next 10 years may teach us that the plasma atmospheres of sun and earth affect the one we breathe, our weather, and our climate. Twenty years, then, is a good time at which to pause and think, to ask whether the reasons we first undertook to do solar-system plasma physics are still valid, and whether we have found new ones. We should try to fathom what lies ahead and how best to equip and organize ourselves to meet our future. In this spirit, then, we present our report on solar-system magnetohydrodynamics–the study of large-scale plasma phenomena in the solar system beyond the sun and one part of the larger discipline of solar-system plasma physics.

Many studies have treated individual topics in solar-system magnetohydrodynamics separately. However, we believe this is the first time that they have been reviewed together. We hope it will not be the last. In Section 7.2, we discuss some outstanding scientific questions posed by our subject. We hope that detailed planning for solar-system plasma physics will go forward vigorously and that these and other scientific problems, well posed and integrated into a wide context, will help guide such planning. In Section 7.3, we present our general conclusions concerning the overall status of solar-system magnetohydrodynamics, and in Section 7.4, our recommendations. Sections 7.3 and 7.4 may be read independently of Section 7.2 but should be read together.

7.2 OUTSTANDING SCIENTIFIC PROBLEMS IN SOLAR-SYSTEM MAGNETOHYDRODYNAMICS

We will present detailed scientific reviews of many topics in solar-system magnetohydrodynamics (MHD) in Volume 2 of this report. In this section, we highlight these detailed considerations by a selective review of some oustanding problems posed by our subject. Our purpose is twofold. First, we believe that well-posed scientific problems can help us to decide what to do. Second, we hope that the outlines of the emerging discipline of solar-system plasma physics, of which solar-system MHD is a part, can be perceived from our list of problems.

In Section 7.2.1, we discuss the solar wind and heliosphere, and in Section 7.2.2, the interaction of the solar wind with planets and comets. In Section 7.3, we summarize the general status of research in solar-system MHD.

7.2.1 The Solar Wind and Heliosphere

7.2.1.1 The Solar Wind

The outer layers of the sun are a convective heat engine producing both large- and small-scale hydromagnetic motions. These motions create a dynamo magnetic field, in itself a poorly understood phenomenon. These solar magnetic fields do not spread uniformly over the solar surface but concentrate themselves in intense isolated flux tubes that somehow resist the tendency to expand. In addition, the turbulent motions in the outer convective layer of the sun heat the solar corona. Thus, activity at the solar surface sets the stage for the generation of the solar wind by providing a complex magnetic topology from which the heated solar corona must escape into interplanetary space. Since the coronal pressure greatly exceeds that of the interstellar medium, that part of the corona not strongly confined by the solar magnetic field expands in a flow that is subsonic near the sun and supersonic throughout interplanetary space. This solar wind carries a part of the solar magnetic field throughout the solar system; the wind speed also exceeds the Alfvén speed—a characteristic speed for magnetic disturbances in a plasma. Thus the solar wind is a supersonic, super-Alfvénic, strongly ionized flow that transports plasma, energy, angular momentum, and magnetic field past all the planets of the solar system. It is finally decelerated to subsonic speeds by its interaction with interstellar matter at a distance of a few hundred astronomical units. One definition of the heliosphere is simply the region of flow of solar origin; its boundary, the heliopause, separates the solar wind and interstellar plasma.

Expanding hydromagnetic flows, like the solar wind, are a common astrophysical occurrence. The plasma in galactic halos and globular clusters may expand in similar fashion. Relativistic winds have been proposed for pulsars and radio galaxies. All stars that have convective outer layers like that of the sun are inferred to have stellar winds and heliospheres. The solar wind has carried off much of the sun's original rotational angular momentum over the sun's lifetime; other stars, like the sun, are also observed to rotate slowly. Stars with radiative outer layers are observed to have stellar winds driven by radiation pressure.

The solar wind is the only astrophysical wind accessible to *in situ* measurement. Since 1960, the solar-wind flow speed, density, temperature, chemical composition, ionization state, and magnetic field have been studied in great detail near the earth. In the past five years, solar-wind measurements have been extended to within the orbit of Mercury and well beyond the orbit of Jupiter. Since the solar wind has been as completely diagnosed as any laboratory plasma, a detailed theoretical understanding of it is possible.

While idealized models of astrophysical winds are steady, we know the solar wind is highly time variable. Its basic short-term variations are associated with high-speed streams and hydromagnetic shocks, which are in turn related to coronal spatial structures and temporal variations such as solar flares. Interplanetary magnetic structures are also observed to be connected to the complex magnetic structures in the solar corona. Longer-term variability is associated with the roughly 11-year solar cycle; solar cycles differ considerably one to another. Solar and solar-wind variations may be associated with terrestrial weather in some way. Finally, the solar wind has certainly evolved over the lifetime of the sun. It was probably much stronger in the distant past.

Over the past five years, two major achievements in solar-wind research stand out above all others. First is the development of models describing the spatial and temporal evolution of large-scale solar-wind structures, including high-speed solar-wind streams and flare-produced interplanetary collisionless shock waves. These models have significantly improved our understanding of the many solar wind observations at 1 A.U. and have been firmly established by recent simultaneous measurements near the orbits of earth and Jupiter. The second recent major achievement is the rapid evolution of understanding of the relationship between the solar wind and solar coronal holes, attributable largely to the Skylab Coronal Hole Workshops held over the past two years. The realization that high-speed solar-wind streams, and probably most of the lower-speed solar wind, originate in the low-density, rapidly diverging flux tubes of coronal holes has completely reoriented much of solar-wind research, crystallizing many problems that should be attacked in the near future.

There are currently three major outstanding problems in solar-wind research. By far the largest is the coronal expansion problem, which relates the energy flux carried into the corona from lower layers to that carried away from the sun by the solar wind. Understanding coronal expansion requires solution of several subsidiary problems: (a) the description of a rapidly diverging hot plasma expansion in the presence of outward propagating hydromagnetic waves—the transition from a collisional flow at the base of the corona to a collision-free flow at the top is itself a challenging problem; (b) an accurate description of the magnetic-field geometry in coronal holes; and (c) a description of the wave energy flux entering the corona from lower layers. *The entire coronal expansion problem requires a well-coordinated, combined observational and theoretical attack.* The other two solar-wind problems concern the chemical composition and ionization state of the solar wind and the angular momentum lost by the sun to the solar wind. We do not know why the solar-wind chemical state varies dramatically with time. Although comprehensive understanding of the composition and ionization state requires an adequate coronal expansion model, a solid theoretical framework should be developed in the near future using various plausible assumptions about the coronal expansion. The angular momentum transport problem currently awaits better observations of the mean azimuthal velocity of the solar wind, in and out of the ecliptic plane. Finally, our understanding of how the solar wind interacts with the interstellar medium is rudimentary.

7.2.1.2 Hydromagnetic Waves in the Solar Wind

Hydromagnetic waves, the most important class of waves found in the solar wind, cover the entire range of frequencies below the ion gyrofrequency.[1] Hydromagnetic waves are analogous to sound waves

in air but are more complex. They can be classified into fast, intermediate, and slow propagating modes plus two nonpropagating discontinuities, almost all of which have been observed, although some are very rare. The intermediate, or transverse Alfvén, wave dominates the solar wind's hydromagnetic turbulence spectrum half the time. It often has a regular power-law wavelength spectrum. The fast, or magnetosonic wave, is rarely found, consistent with theoretical predictions of its strong damping. Abrupt changes in magnetic–field and plasma parameters are regularly observed; these are a mixture of non-propagating tangential discontinuities and sharply crested nonlinear transverse Alfvén waves. The Alfvén wave intensity is related to solar-wind stream intensity; the turbulence in the compression regions associated with fast streams is highly non-Alfvénic and poorly understood. The amplitude of interplanetary hydromagnetic waves is usually large, making them a motivation for and test of nonlinear turbulence and wave theory.

Studies of correlations between plasma velocity and magnetic-field fluctuations indicate that the Alfvén waves propagate away from the sun—a strong argument that they originate near the sun. If so, one would expect their intensity to decrease with distance from the sun. Preliminary measurements indicate that the energy density of all classes of hydromagnetic structures decreases with increasing heliocentric distance. However, except for this general intensity decrease, and some relations of wave properties to stream structure, little is known about the spatial distribution of interplanetary turbulence. This is true even at the local level, since there is fairly good evidence that interplanetary fluctuations are not planar even on the scale of 0.01 A.U. If their surfaces of constant phase are indeed highly curved, theoretical techniques for calculating wave polarization, propagation, and nonlinear interactions would have to be revised radically.

Two important problems stand out in solar-wind hydromagnetic wave research. *Progress in understanding of the spatial distribution, and subsequently the origins of interplanetary hydromagnetic waves, will require not only refinement of our understanding near-earth orbit but especially exploration near the sun and out of the ecliptic plane.* Secondly, their turbulent wavelength spectrum, and its variation with solar-wind conditions, is poorly understood. *Multiple satellite observations would provide fundamental inputs to the new developments in nonlinear wave and turbulence theories required for an adequate understanding of solar-wind turbulence.*

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[1] Smaller-scale plasma waves in the solar wind are treated in Volume 2 by W. C. Feldman.

In summary, hydromagnetic waves may play a major role in heating and accelerating the entire solar wind and transport significant energy and momentum through it. Furthermore, the solar wind provides an excellent, and to date the primary laboratory, in which the generation and propagation of nonlinear hydromagnetic wave turbulence has been studied *in situ*. Understanding its fully developed turbulent wavelength spectrum would therefore be an important theoretical achievement of general scientific interest. Moreover, understanding the hydromagnetic wave spectrum is essential to an understanding of the propagation and scattering of cosmic rays, to which we next turn our attention.

7.2.1.3 Interaction of Energetic Particles with the Solar Wind

Just as earth's atmosphere and ionosphere shield from our view much of the electromagnetic radiation coming to us from the cosmos, so also does the solar wind distort the spectrum of cosmic-ray particles arriving from our galaxy. Galactic particles, for example, contain in their spectrum and composition information concerning their sources (e.g., supernovae), acceleration, and subsequent propagation through the interstellar medium. However, at energies ≤ 10 GeV/nucleon, where the cosmic-ray energy density peaks, the cosmic-ray spectrum and composition are altered by interaction with the solar wind. To derive the maximum information from cosmic rays we must understand and account for this modulation.

Studies of energetic particle behavior in the solar wind are also of fundamental interest. The cosmic rays in the solar wind have gyroradii that span the full range from very small to very large compared with the scale lengths of the hydromagnetic turbulence in the solar wind. *In situ* measurements of both fields and particles permit us to develop and test theories for the propagation and acceleration of energetic particles over this wide range of scales. This information is not readily obtainable from laboratory experiments and could be scaled to other applications, especially in astrophysics.

Energetic particle interactions with the solar wind are normally considered on three levels:

Modulation Theory To interpret cosmic-ray observations, we use a macroscopic or "fluid" description of the particle behavior, in which their interactions with hydromagnetic turbulence enter only through the elements of a phenomenologically determined diffusion tensor. This description, developed over the past ten years, accounts for many diverse observations, such as the lack of evidence for ionization loss observed in low-energy galactic particles, as well as what otherwise would be a puzzling spectral shape at low energies. It is also compatible with recent Pioneer 10 and 11 measurements of the radial gradient of cosmic-ray intensity.

Propagation Theory Here we attempt to determine the diffusion tensor from observations of the hydromagnetic turbulence in the solar wind; at the same time, we must use the measurements to justify the diffusion approximation. In this area, we are far less successful. For example, our current theories predict that low-rigidity particles should be scattered in pitch angle relative to the solar-wind magnetic field far more than is actually observed. This disagreement is not only puzzling but may be fundamental, since our theories use some of the most advanced plasma physical techniques. In fact, for a particle propagation below a few MeV/nucleon, there is no adequate theory at all.

Acceleration Theory Here we consider the acceleration of energetic particles in the hydromagnetic turbulence and in shock fronts in the solar wind. Our theories here are relatively primitive. For example, in calculating statistical acceleration rates, only standard plasma turbulence theory is used, which has difficulties describing propagation at low rigidities, precisely where acceleration theory is applied.

Two objectives are most pressing in solar-wind cosmic-ray research. First, the theories of the interaction of cosmic rays with solar-wind turbulence appear to be inadequate at low energies, when the particle Larmor radii are small compared with the scale lengths of the turbulence. A new theoretical approach to the coupling of hydromagnetic turbulence to energetic particles may be called for. Second, our observations may be biased because they have all been made near the ecliptic plane. For example, galactic cosmic rays observed near the earth may enter the inner solar system over the solar poles. *Measurements at high heliographic latitudes are required for an understanding of modulation and to deduce from observation reliable information about the primary galactic spectrum and its sources.* Indeed, at high heliographic latitudes, we may be able to observe cosmic rays that have low energies in the interstellar medium, which appear to be excluded from the inner solar system near the ecliptic plane. Measurements at higher latitudes would also allow us to study

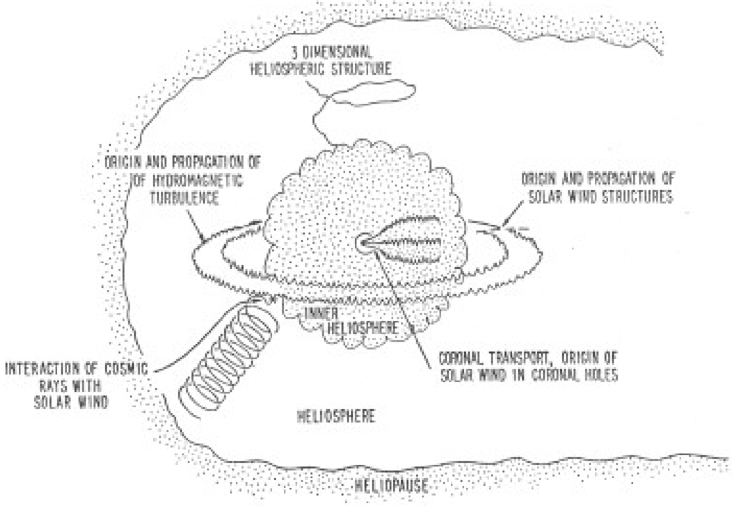

FIGURE 7.1 Critical problems of heliospheric physics. Note that the inner generation regions of the solar wind have been expanded so that they may be seen.

propagation and acceleration of cosmic rays under conditions differing substantially from those near the eciptic plane, thereby providing a fundamental test of our understanding.

This concludes our selective review of the solar wind, its hydromagnetic turbulence, and its interaction with cosmic rays. Figure 7.1 illustrates schematically some of the important scientific questions that have emerged in the past few years. We now discuss how the solar wind interacts with the objects in the heliosphere.

7.2.2 Interaction of the Solar Wind with Planets and Comets

The planet's magnetospheres are cavities carved out in the solar-wind flow by their intrinsic or induced magnetic fields. The boundary separating solar wind from magnetosphere is the magnetopause. Within the magnetopause, the magnetic field organizes the behavior of charged particles, plasma waves,[2] and electrical currents; it traps energetic particles to form radiation belts and confines low-energy plasma escaping into space; finally, it transmits hydromagnetic stresses between the magnetosphere via the partially conducting ionosphere to the upper atmosphere of the planets.

The earth's magnetosphere was discovered in 1958. In the past several years, Pioneers 10 and 11 traversed the magnetosphere of Jupiter, and Mariner 10 discovered an unexpected, surprisingly powerful, and highly time variable magnetosphere at Mercury. Low-frequency radio bursts recently detected from Saturn suggest that Saturn has a magnetosphere. Scaling arguments suggest that Saturn, Uranus, and Neptune all have large magnetospheres. On the other hand, the solar wind interacts directly with the atmospheres and ionospheres of Mars and Venus and the surface of the moon, because these planets have weak intrinsic magnetic fields. Little is known or guessed about the solar wind's interactions with Pluto. The solar wind interacts with comets to form a long tail.

In astrophysics, the concept of magnetosphere has been generalized to any plasma envelope of a compact central body. While every class of natural object has its important distinguishing characteristics, the magnetospheres of tailed radio galaxies may share common features with planetary magnetospheres. The distant portions of pulsar and some radio galaxies' magnetospheres may resemble the solar wind's heliosphere. Thus, the resemblances between astrophysical and planetary magnetospheres could eventually motivate a unified theoretical attack on them. Likewise, the concept of comparative magnetospheric studies should contribute to the theoretical understanding of the physical processes involved.

Most magnetospheres exhibit different variations on a common theme: wherever nature creates a magnetosphere, she arranges that magnetic energy stored in them be suddenly released, accelerating a small subset of charged particles to high energy. On the sun, such events are called solar flares; on earth and Mercury, substorms. The electromagnetic radiation generated by the few particles accelerated to relativistic energies might be the dominant observable in astrophysical magnetospheres; on the other hand, the energy storage and release mechanisms and the microscopic properties of the particle acceleration regions of planetary magnetospheres can be probed *in situ*.

7.2.2.1 Earth's Magnetosphere

Earth's is the best understood of all magnetospheres. During the past 19 years, terrestrial magnetospheric research has passed through highly successful stages of discovery and exploration, during which it has

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[2] Plasma waves in planetary magnetospheres are discussed in Volume 2 by S. D. Shawhan.

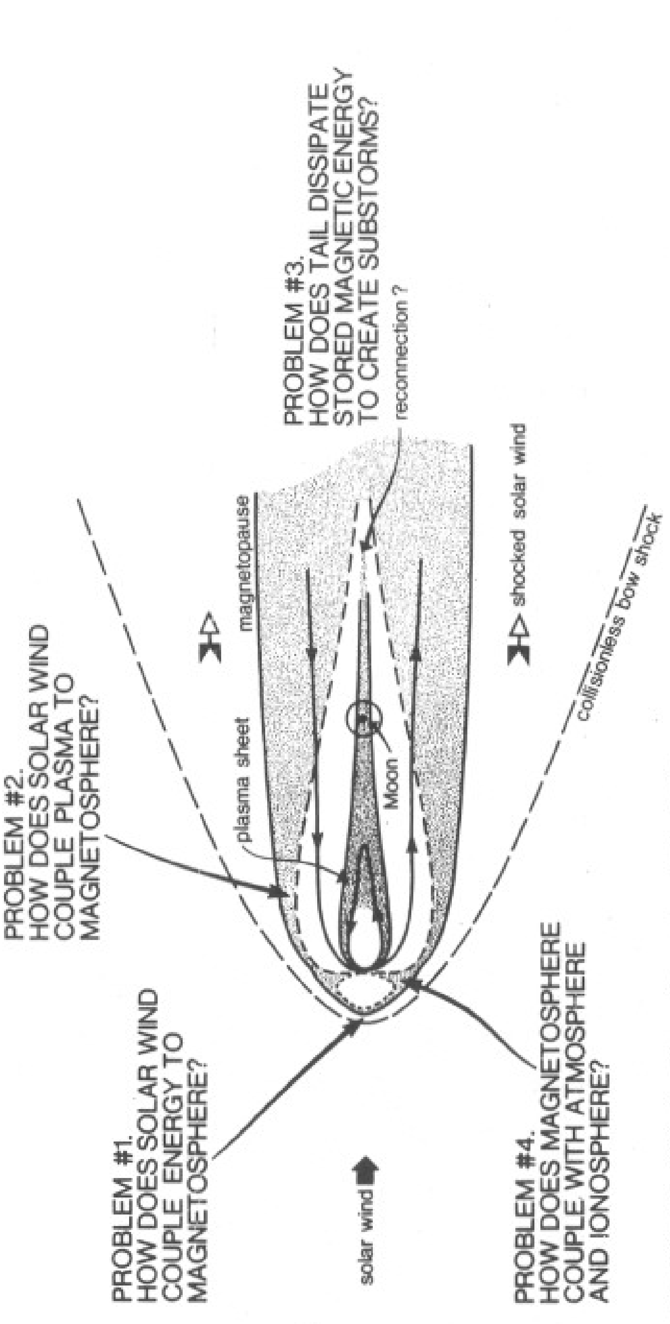

FIGURE 7.2 Critical problems of magnetospheric physics.

achieved a good phenomenological description of, and has identified most and begun to understand many of, the fundamental physical processes regulating our earth's magnetic interaction with the solar wind. In so doing, it has learned to use a wide range of research tools, including satellite, rocket, aircraft, and ground-based measurements, which, together with theory, now must be devoted to its next objective: *a comprehensive quantitative understanding of the cause and effect relations between time-dependent magnetospheric processes.*

Now we list four problems sufficiently general that they may serve as organizing principles for future systematic theoretical and experimental research in magnetospheric physics. These are illustrated in Figure 7.2.

Problem 1: Effect of the Solar Wind on the Topography, Topology, and Dynamics of the Magnetosphere Since the earth's magnetosphere acts like a blunt body standing in the supersonic solar wind, a collisionless bow shock[3] stands upstream of the magnetosphere in the solar wind. The magnetopause is the boundary surface enclosing the magnetospheric cavity. The region between the magnetopause and bow shock containing shock-heated flowing plasma is called the magnetosheath. Magnetosheath energy, momentum, plasma, magnetic and electric flux, and electric currents are coupled to the magnetosphere across the magnetopause. The coupling rate is set by microscopic processes in the thin magnetopause. Task number one of magnetospheric physics is to determine these magnetopause transport properties, how they vary when the upstream solar wind changes, and the global response of the magnetosphere to variations in transport processes across the magnetopause.

It was suggested in 1961 that the solar-wind magnetic field plays a significant and perhaps the dominant role in coupling all the above quantities across the magnetopause, through the magnetic-field line-reconnection process.[4] Magnetopause reconnection has not yet been conclusively identified, and recent measurements raise serious doubts as to whether it is as effective as once thought. Other transport mechanisms, such as turbulent viscosity, may be equally important. Identification of magnetopause reconnection has been hampered by a lack of theories that specify the distant signatures of reconnection

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[3] For a discussion of the microscopic turbulent structure of the bow shock, see the paper in Volume 2 by R. W. Fredericks and E. W. Greenstadt.

[4] For a discussion of reconnection, see the paper in Volume 2 by B. U. O. Sonnerup.

most likely to be observed by satellite. *Spatially resolved studies of the plasma, magnetic field, and microscopic turbulence on and near the magnetopause as a function of magnetosheath parameters are necessary to determine how magnetopause transport regulates the magnetosphere's behavior.*

In addition, complementary studies of the global response of the magnetosphere to variations in the solar wind must be continued. *It is highly desirable that the magnetosphere's time-dependent variations be studied simultaneously with those in the solar wind.* It is essential to discern which features are governed directly by variations in magnetopause transport and which are integral responses to distant conditions and past history. At present, the macroscopic behavior of the magnetosphere has been interpreted primarily in terms of a magnetopause reconnection model. Should magnetopause reconnection prove unimportant, a considerable rethinking will be necessary.[5]

Problem 2: Solar-Wind Plasma Entry into the Magnetosphere Task number two of magnetospheric physics is the experimental determination and quantitative theoretical understanding of the entry of solar plasma into the magnetosphere and of where it goes after entry as a function of solar-wind conditions. Some plasma of solar-wind origin flows down field lines into the dayside ionosphere at high magnetic latitudes; some has been observed flowing tailward in a thin boundary layer next to the magnetopause over the earth's magnetic poles; this boundary layer becomes thicker at the distance of the moon; where does it close and fill the tail with plasma of solar-wind origin? *To answer the solar-wind entry problem, multiple high-inclination high-apogee satellite missions over the geomagnetic poles, coupled with low-altitude studies, are desirable.*

Problem 3: Plasma and Energy Storage and Release Mechanisms in the Earth's Magnetospheric Tail The solar wind stretches out the earth's magnetic field into a long magnetic tail extending perhaps 1000 earth radii downstream. The magnetic tail is divided into northern and southern lobes of opposite polarity, separated by a sheet of hot plasma that is thought to be the hot plasma source for the inner magnetosphere. The tail and plasma sheet give rise to the most fundamental instability of the magnetosphere—the magnetospheric sub-

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[5] A revision in our picture of nose reconnection may be significant to astrophysics, where it is often assumed that reconnection occurs if the magnetic-field topology is appropriate.

storm—in which magnetic energy accumulated in the tail is explosively converted to particle kinetic energy, with a host of important consequences, such as greatly enhanced auroral particle precipitation and light emission, and the injection and/or acceleration of energetic electrons and ions into the inner magnetosphere and radiation belts[6] and the acceleration of some particles to relativistic energies in the tail.

The substorm is very likely the magnetosphere's fundamental mode of energy dissipation; its study, broadly conceived, constitutes task number three of magnetospheric physics. What happens preceding, during, and after a substorm? How does the occurrence of substorms depend on the magnetosphere's past history? Is the substorm a direct response to solar-wind variations, or can it be independently triggered? What in fact triggers the substorm? Magnetic-field reconnection may dissipate much of the substorm's energy. However, lack of detailed theories on how reconnection operates in the geomagnetic tail prevents a conclusive answer. Where in the tail does the substorm first start? Answers to the last question range from near the earth to beyond the moon's orbit. A global, but partial view, of the behavior of the distant tail has been obtained from the behavior of the earth's polar cap and auroral regions, since the magnetic field threading them penetrates deep into the tail. Recent satellite photographs of the earth's polar cap and auroral zone have enabled us to discern the auroral signatures of substorm events occurring perhaps deeper in the tail than spacecraft regularly penetrate. In addition, radar studies of ionospheric motions have given information on the electric fields on auroral and polar-cap magnetic-field lines. At present, both techniques have insufficient time resolution to track the time development of a substorm property. However, improvements are feasible in both cases.

The most meaningful studies of the dissipation processes in the geomagnetic tail require

- *Simultaneous standarized measurements of many plasma parameters in the near and distant tail,*
- *Coordination with polar-cap and auroral-zone measurements with adequate geographical coverage and temporal resolution, and*
- *Knowledge of the simultaneous behavior of the solar wind.*

The earth's magnetic tail beyond the orbit of the moon (60 R_e) has

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[6] The radiation belts of the earth are discussed in detail in Volume 2 by L. R. Lyons.

not been explored by spacecraft, although it has been twice penetrated briefly by Pioneer missions. Exploration of the earth's tail and wake beyond approximately 100 R_e downstream might provide answers to several first-order questions, such as, what fraction of the energy and plasma injected at the magnetopause enters the inner magnetosphere, and what fraction escapes downstream; and how many ions of ionospheric and atmospheric origin escape downstream in the solar wind? Furthermore, some recent research suggests that much of the substorm energy dissipation may take place well beyond the moon's orbit.

Problem 4: Atmosphere–Ionosphere–Magnetosphere (AIM) Interactions The fourth major task in magnetospheric physics is to determine how the earth's atmosphere, ionosphere,[7,8] and magnetosphere couple one to another and thereby regulate each other's time-dependent behavior. The AIM interactions can be subdivided into a number of subsidiary problems. The first may be termed the electrodynamic coupling problem. How do the flows in the magnetosphere and ionosphere–atmosphere, each of which produce an electric field, influence each other? The coupling between these two flow and electric-field systems is carried out in part by means of electrical currents that flow along magnetic-field lines between them. In the time-dependent magnetosphere, knowing the electric field is fully as important as knowing the magnetic field. The electrodynamic coupling problem has been significantly advanced by our recently developed capabilities to measure *in situ* electric fields and currents. These global measurements are beginning to give us an appreciation of just how dynamic the interchanges between magnetosphere and ionosphere–atmosphere are. There are at present two serious impediments to full understanding of electrodynamic coupling. First, the role of upper-atmospheric winds, while certainly important, remains uncertain. By their interaction with the partially conducting ionosphere, upper-atmospheric winds can generate, or be generated by, magnetospheric motions. Secondly, the physics of the electrical currents parallel to magnetic-field lines that connect the separate domains of magnetosphere and atmosphere–ionosphere must be clarified. The observations of beams of energetic electrons moving paral-

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[7] Some problems in ionospheric plasma physics are discussed in Volume 2 by D. T. Farley.

[8] Other problems in ionospheric research and communications applications are discussed in Volume 2 by F. W. Perkins.

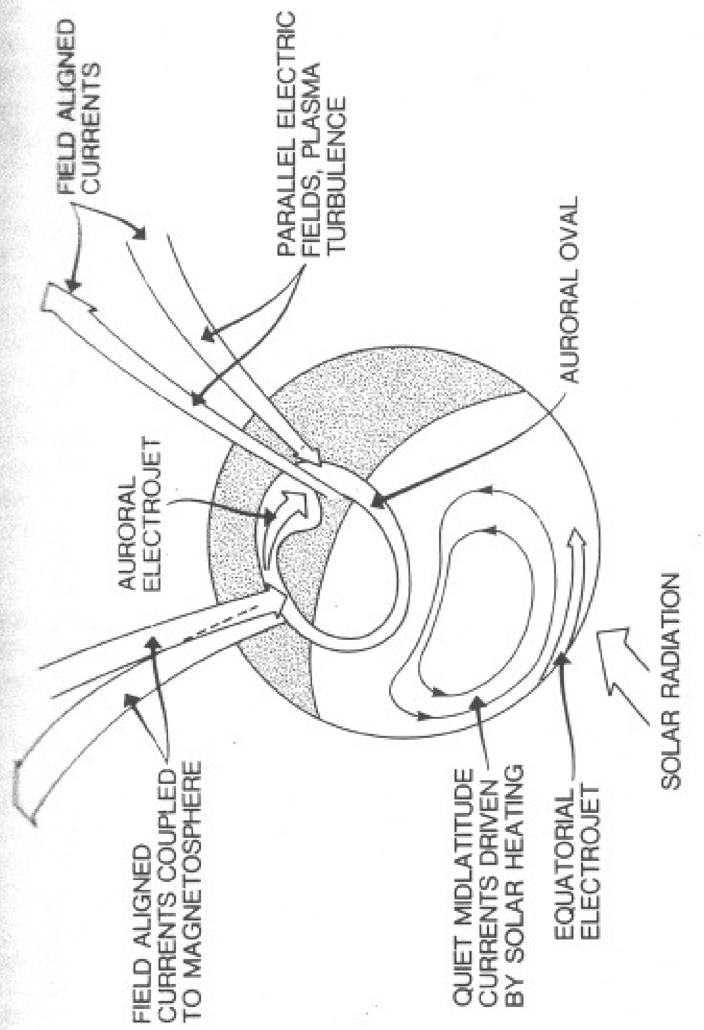

FIGURE 7.3 Electrodynamic coupling.

lel to the magnetic field suggest that parallel electrical currents create large parallel electric fields either by a noncollisional resistivity created by microscopic plasma turbulence or by shocklike localized "double-layer" electric fields.[9] These parallel electric fields spoil the simple mapping of electric potential between atmosphere–ionosphere and magnetosphere, thereby invalidating the use of hydromagnetic theory, and may be involved in the formation of the long striated arcs of the aurora. Auroras are not only of great historical and aesthetic interest, but they are energetically significant and involve highly nonlinear electrodynamic coupling processes. Figure 7.3 is a schematic of the current and wind systems involved in the electrodynamic coupling of magnetosphere, ionosphere, and atmosphere.

The important closed chain of cause and effect relationships involving magnetic field-aligned currents, electric fields, the ionosphere and magnetospheric plasmas, and atmospheric winds must be understood quantitatively and self-consistently. To this end, satellite missions that directly measure the physics of the field-aligned current region, while simultaneously monitoring—together with ground-based diagnostics—the state of the atmosphere and ionosphere below it are highly desirable. In addition, the self-consistent interaction between the many variables listed above makes the electrodynamic coupling problem susceptible to, and needful of, numerical modeling. On a global scale, such models relate the atmospheric–ionospheric wind patterns to magnetospheric motions. On a smaller scale, they may illuminate the problem of auroral arcs. Finally, active geophysical experiments that break into the AIM causal chain by introducing known perturbations and detecting nature's response will be particularly valuable to the electrodynamic coupling problem.

How the plasma escapes from the ionosphere to the magnetosphere, where it goes and what it does is the second important topic in AIM interactions. Little has been done to explore the interaction between the hot magnetospheric plasma and the cooler ionospheric plasma, which flows upward into the magnetosphere. Information on the hot–cold balance is proving essential to the understanding of plasma turbulence occurring both above the ionosphere and deep in space. At high latitudes, a low-energy analog of the solar wind is known to exist. This polar wind consists of ionosphereic H^+ and He^+, which flow away from the earth at supersonic speed. Furthermore, recent observations of energetic (1–5 keV) O^+, He^+, and H^+ apparently accelerated in and then streaming upward from the auroral regions suggests that the electrodynamic coupling processes forming the aurora may also be an important new energetic plasma source for the magnetosphere.

The third, most undeveloped and yet potentially most far-reaching, problem in AIM interactions is the coupling of the solar wind and magnetosphere via the ionosphere and upper atmosphere to the lower atmosphere. Any potential relations between solar and solar-wind activity and weather and climate will probably involve magnetosphere–ionosphere–atmosphere coupling.

General Remarks We believe that well-posed scientific problems, such as those listed above, should increasingly serve as organizing principles for future research. Our four key problems above emerged from exploratory research using spacecraft conceived largely in the 1960's, well before these problems were clearly defined.[10] Continuing acquisition and analysis of data from these spacecraft has put these and other problems in sharp focus. Thus, new spacecraft missions and multiple or coordinated spacecraft mission campaigns designed using our current knowledge should significantly advance our understanding of the magnetosphere in the 1980's.

We believe terrestrial magnetospheric physics should have a high scientific priority within solar-system plasma physics for two reasons. First and foremost, earth is our home. Second, because of our relatively complete understanding and the comparatively low cost of terrestrial magnetospheric experiments, magnetospheric research, imaginatively conceived and sympathetically administered, can be a seed bed of innovation for the eventual use by all of solar-system

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[9] In the past year, double layers were created in the laboratory for the first time and may also have been identified on auroral-field lines.

[10] The recent program of the NASA Office of Solar-Terrestrial Physics in the earth's magnetosphere has been based on continued acquisition and analysis of data from ISIS-2 (launched April 1971), IMP-7 (September 1972), IMP-8 (October 1973), Atmospheric Explorer C (December 1973), Hawkeye-1 (June 1974), and Atmospheric Explorer-E (November 1975). IMP-7 and -8 have solar wind as well as magnetospheric objectives. Atmospheric Explorers C and E and Hawkeye-1 will re-enter the earth's atmosphere within the year. Their payloads were approved by the NASA Space Science Steering Committee years before launch [August 1966 (ISIS-2), April 1967 (IMP-7 and -8), and January 1970 (Atmospheric Explorers C and E)] and conceived before that. *Thus they were designed well before the scientific problems they helped to clarify were clearly defined.* All the above spacecraft continue to provide important new information; indeed without continuing data acquisition and analysis, research in magnetospheric physics would have been significantly impeded.

plasma physics. Finally, the desire for multiple or coordinated spacecraft missions, together with the need for concurrent solar-wind monitoring and ground-based diagnostics, makes terrestrial magnetospheric physics a fruitful arena for international cooperation in space research.

7.2.2.2 Jupiter's Magnetosphere

Jupiter's magnetosphere, discovered 20 years ago by radio astronomers, has recently been traversed by the Pioneers 10 and 11 spacecraft. It is currently the only object in the cosmos for which inferences drawn from remote astronomical observation can be compared with direct *in situ* measurements of its neutral atom, plasma, and magnetic-field environment.[11] Because Jupiter's magnetosphere is a rotating magnetized source of radio emissions and relativistic particles that are modulated at its rotation frequency, it may resemble astrophysical cosmic-ray and radio sources such as pulsars.

Pioneers 10 and 11 enabled three important conclusions to be reached. First, Jupiter's outer magnetosphere is radially stretched into a highly time-variable disklike configuration that differs fundamentally from earth's outer magnetosphere. Jupiter's outer disk region is modulated at Jupiter's 10-hour rotation period and, in addition, changes drastically on time scales of a few days to a week. Since the time scale for these gross changes in Jupiter's outer magnetosphere is comparable with the duration of flyby missions, flybys are so severely time-aliased that they probably cannot resolve the cause of the time dependences. Second, Jupiter's outer magnetosphere generates—or permits to escape—such intense fluxes of relativistic electrons that Jupiter is the dominant source of 1–30-MeV cosmic-ray electrons in the heliosphere. Third, Jupiter's satellite, Io, has several extremely important effects on Jupiter's magnetosphere. Io absorbs some radiation belt particles and accelerates others; Io modulates the Jovian decametric radii emissions; and, most importantly, Io is a source of neutral atoms and by inference a heavy-ion plasma that may significantly affect the hydromagnetic flow in Jupiter's magnetosphere.

The Jovian radiation belts are considerably better understood than the remainder of its magnetosphere. Energetic ions and electrons diffuse radially inward, gaining energy thereby, subject to losses to absorption by Jupiter's satellites and probably to scattering by

[11] We expect the magnetospheres of Saturn and Uranus to join Jupiter in this class within the next decade.

microscopic plasma turbulence. Those electrons that diffuse as far inward as two Jovian radii from Jupiter's center, and reach relativistic energies thereby, then lose energy by the synchrotron process to the Jovian decimetric radio emissions. Our good understanding of the Jovian radiation belts depends in part on the strong state of terrestrial radiation belt theory. On the other hand, how Jupiter generates the relativistic electrons that fill the heliosphere remains a mystery.

Hydromagnetic theories of Jupiter's outer magnetosphere are in a formative stage. It has been suggested that a heavy-ion plasma from Io and hydrogen escaping from Jupiter's ionosphere first radially diffuses outward and then is flung centrifugally outward by Jupiter's rapid rotation to form a planetary version of the solar wind, which then stretches Jupiter's outer magnetic field into a disk.

While the four fundamental questions of magnetospheric physics posed above for earth are undoubtedly important for Jupiter, we have not yet identified many of the physical processes relevant to them in the Jovian magnetosphere.[12] Thus, the questions are not so clearly posed for Jupiter as for earth. If Jupiter has a planetary wind, its magnetopause should be more structured and time-variable than earth's, as observed. Consequently, how the planetary wind might interact with the solar wind is poorly understood. Jupiter has three plasma sources: ionosphere, Io, and solar wind. Quantitative theories of all three plasma sources are at present very rough. Atmospheric–ionospheric–magnetospheric interactions are important at Jupiter. Turbulent winds in Jupiter's upper atmosphere are thought to couple to turbulent hydromagnetic motions in its magnetosphere. This pro-

[12] Pioneers 10 and 11 were destined to be "successful" because they were the first spacecraft to go to Jupiter. However, greater attention to physical questions would have significantly improved their scientific output at no increase in cost. A case in point is the 1971 JPL Workshop, called in an emergency atmosphere to evaluate the radiation hazard to the spacecraft. The JPL Workshop stimulated the creation of refined radiation belt models prior to encounter. Suppose the workshop had been held in 1968; good models would have been available in 1970, suggesting that different experiments go on board the spacecraft. It is no criticism of the four high-energy particle teams on board—each of which did a creditable job—to say that at least two of the four were redundant. A more balanced experiment would have included a radio/plasma wave detector and the capability of detecting flowing low-energy plasma within the magnetosphere. By this last oversight, the basic hydromagnetic structure of Jupiter's outer magnetosphere was not resolved by Pioneers 10 and 11. It is small consolation that these oversights will be corrected with subsequent spacecraft. Because of the long interval between experiments, time in which the physics could have been elucidated was lost, and lost time means diminished scientific vitality.

cess may diffuse energetic particles inward to its radiation belts and low-energy plasma of Io and ionospheric origin outward into its outer magnetosphere. However, even the basic structure of Jupiter's polar cap and auroral ionosphere is very poorly understood. It is not known whether Jovian auroras exist.

Jupiter's magnetic tail was not traversed by Pioneers 10 and 11. Inferences from scaling laws and from the observed heliospheric propagation of Jovian cosmic-ray electrons suggest that it may be several astronomical units long. If so, Jupiter's magnetic tail and the solar wind are comparable in scale. Thus Jupiter's magnetosphere might respond time-dependently to entirely different solar-wind perturbations than does earth's. Because the Jovian magnetopause and tail are poorly understood, we do not know whether earthlike substorms occur at Jupiter. If they do, they would last several days to a week, again comparable with a flyby duration.

Understanding the time-dependent processes in Jupiter's magnetosphere requires an orbiter capable of diagnosing the magnetospheric plasma at distances from a few to more than 100 Jovian radii at a variety of magnetic longitudes, including the magnetic tail region, and close coordination between experiment and theory.

7.2.2.3 The Magnetosphere of Mercury

Mariner 10 discovered an unanticipated magnetosphere at Mercury. Its three flyby encounters with Mercury revealed a bow shock standing in the solar wind and permanent magnetosphere whose shape is similar to earth's. The average distance from the center of Mercury to the subsolar point on Mercury's magnetopause is 1.4 Hermetian radii, consistent with Mercury's measured dipole moment and the strength of the solar wind at the orbit of Mercury. Thus, Mercury occupies much more of its magnetosphere than earth or Jupiter, precluding the formation of energetic-particle radiation belts in an undistorted dipolar magnetic-field region. On the other hand, Mercury may have substorms similar to earth's. Intermittent intense bursts of high-energy particles were observed in Mercury's magnetic tail.

The four fundamental questions posed for earth and Jupiter will have different answers for Mercury. Because Mercury is closer to the sun, both the solar-wind plasma energy flux and magnetic field are stronger at Mercury than at earth. Magnetic-field reconnection can still impose a large electric potential, consistent with the energies of the observed accelerated particles, across Mercury's magnetosphere despite its small size. On the other hand, because the ion Larmor radius in Mercury's magnetosheath is a larger fraction of its magnetospheric scale size than at earth, turbulent hydromagnetic viscosity could be important at Mercury. Mercury and earth's magnetospheres should have two different ratios of reconnection and viscous transport rates. Because of Mercury's large size relative to its magnetosphere, absorption by the planet eliminates a trapped radiation zone and probably strongly affects the hydromagnetic flow within the magnetosphere. The absence of a significant ionosphere at Mercury may mean that the electric fields generated by the hydromagnetic flow might couple directly to the resistive surface of the planet, making the flow fundamentally different from those at earth or Jupiter. If Mercury's surface is also a plasma source, plasma composition measurements might indicate the surface composition. Mercury's is the only known planetary magnetosphere with a possible direct surface coupling.[13] Substorms in Mercury's magnetosphere, the smallest in the solar system, last minutes; earth's last hours; and those in Jupiter's, the largest in the solar system, would take days, if they occur.

An exploration by an orbiter is necessary for improved understanding of Mercury's magnetosphere. The duration of flybys at Mercury is so short that we only have hours of measurements in Mercury's vicinity. With suitably high time-resolution instrumentation, a Mercury orbiter could study an order of magnitude more substorms per unit time than at earth, sampling them relatively deeply in its tail. It would also monitor the solar wind close to the sun. All in all, a Mercury orbiter could be a cost-effective test of the scaling laws for planetary magnetospheres.

7.2.2.4 The Magnetospheres of Saturn, Uranus, and Neptune

Both Saturn and Uranus are scheduled for a first flyby reconnaissance in the 1980's. Saturn almost certainly has and Uranus most probably has a substantial magnetosphere. Low-frequency radio bursts—similar to Jovian decametric radio bursts—have been detected from Saturn. Radio emissions from Uranus have also been reported with less certainty. Empirical scaling arguments suggest that Saturn, Uranus, and Neptune have surface magnetic-field strengths the order of 1 G, implying that each planet has a large magnetosphere with a magnetopause radius exceeding ten times the planetary radius. Their magnetospheric properties have been estimated assuming simple

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[13] Such coupling might also occur with magnetized neutron stars.

extrapolation from earth magnetospheric physics. Given the success of this procedure with the Jovian radiation belts, a detailed predictive model of Saturn's radiation belts may be worth the effort. However, because Saturn, Uranus, and Neptune all rotate rapidly, their outer magnetospheres may resemble Jupiter's more than earth's. Saturn's satellite Titan has a massive atmosphere that could be an important source of magnetospheric ions, just as Io's atmosphere is at Jupiter. While Io is in the relatively quiet inner region of the Jovian magnetosphere, Titan may be in a region corresponding to the outer time variable zone of Jupiter's magnetosphere. The rotation axis of Uranus, which unlike all other planets lies nearly in the ecliptic plane, will be directed along the sun–Uranus line in 1988. If Uranus has a dipolar magnetic field like all others known, its dipole axis will be aligned more or less along its rotation axis. Uranus probably provides the opportunity to explore the only "pole-on" magnetosphere in the solar system.[14]

The solar wind is far more time variable in the outer solar system than it is near earth. The interaction and steepening of fast streams lead to regions of strong solar-wind compressions and rarefaction. Therefore, Saturn's and Uranus's magnetospheres may be at least as, and possibly more, time variable than Jupiter's.[15] The effects on the magnetospheres of Uranus and Neptune due to ionization of intersteller neutrals in their vicinity should be studied. Interstellar neutrals might compete with the solar wind in determining their magnetospheric properties even at the present epoch, which is characterized by anomalously low interstellar densities in the solar neighborhood. At other epochs, the interstellar source might possibly dominate, especially when the heliosphere is immersed in a high-density interstellar cloud and when even earth's magnetosphere might be affected.

7.2.2.5 The Interaction of the Solar Wind with the Moon, Venus, Mars, and Comets

A body with an intrinsic magnetic field too weak to deflect the solar wind does not have a classical magnetosphere. Since the moon has little or no atmosphere, the solar wind impacts the moon's surface directly and is absorbed. The lunar regolith contains a historical record of the solar wind that extends over four billion years. The moon's weak magnetic field was created very early in the solar system and differs considerably from the continuously generated dynamo magnetic fields at other planets. Thus, the moon's fields may tell us what to expect for the magnetic fields on other planetary bodies without dense atmospheres that are unable to support dynamo action.

Unlike the moon, Venus has a dense atmosphere, but, like the moon, very little shielding due to an intrinsic magnetic field. The solar wind probably affects the mass, species, and energy balance of the upper atmosphere of Venus. Venus also has a magnetic tail, which may be due to induction, whereby the solar-wind electric field drives currents in the Venusian ionosphere that then create a magnetic field. The most recent investigations of the interaction of Venus with the solar wind were made by Soviet spacecraft in highly elliptical orbits about Venus. Although previous magnetic measurements could be interpreted in terms of a weak intrinsic magnetic field, the Soviet investigators maintain that their results are inconsistent with an intrinsic magnetic field down to altitudes of 1500 km above the surface of Venus. The position of Venus's bow shock has been used to argue that as much as 30 percent of the solar wind flowing across a Venusian cross section impacts its ionosphere. Soviet plasma measurements show that ions from the ionosphere of Venus are picked up by the solar wind.

Unlike Venus, Mars appears to have a magnetic field sufficiently strong to stand off the solar wind most of the time; its extrapolated magnetopause is usually well above the ionosphere. However, there is also evidence that the solar wind may interact directly with the ionosphere of Mars, perhaps intermittently. Again, Soviet plasma measurements can be interpreted in terms of ion pickup by the solar wind.

Comets may be thought of as gravitationally unbound expanding neutral and plasma matter that interacts with the solar wind. Comets very likely have little or no intrinsic magnetic field, but they do have long, probably induced magnetic tails stretched out by the solar wind, that first suggested the possible existence of plasma flowing outward from the sun. Lyman-α measurements show that the neutral hydrogen emitted by a comet is ionized and blown downstream by the solar wind, a process that presumably operates at Mars and Venus as well.

[14] This currently unique geometry has possible application to the earth's magnetosphere during the geologically frequent occurrences of geomagnetic-field reversals during which earth's dipole axis might not be pole-aligned. Studies of the interaction of the solar wind with Venus and Mars might also yield similar insights.

[15] This suggests that flybys of Saturn and Uranus also might be unable to resolve the causes of their time dependences.

The problem currently most critical to an understanding of the hydromagnetic envelopes of both Venus and Mars is to resolve the relative importance of intrinsic and induced magnetic fields. Knowledge of their intrinsic dipole moments is important to planetary dynamo theory. The magnetic field of Mars is the more firmly established, but its dipole moment and orientation are in doubt. To separate intrinsic from induced fields, it is necessary to determine through continuous monitoring the magnitudes and delay times of their ionospheric responses to solar-wind variations. Soviet results indicate a 2–5-h delay between solar-wind perturbation and ionospheric response at Venus. How the solar wind affects the mass and energy balance of the upper atmospheres of both Mars and Venus is another critical problem. Because comets are gravitationally unbound, these last effects have even greater importance for comets.

The theoretical and experimental programs for Venus and Mars are at an early exploratory phase. The Pioneer Venus mission scheduled for 1978 will provide the United States with a large variety of highly resolved measurements close to Venus. Mars deserves similar treatment. *Although the United States has orbited many spacecraft about Mars, only the Mariner 4 flyby included instrumentation to study the interaction of Mars with the solar wind.*[16] *Inclusion of such instrumentation on a future orbiter is desirable.*

Despite the many unanswered questions, our ignorance of the interaction of Mars and Venus with the solar wind pales in comparison with our ignorance of comets. To define the basic properties of the solar wind's interaction with a comet, a rendezvous reconnaissance would be needed.

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[16] This lacuna could have other implications. At earth, atmospheric–ionospheric–magnetospheric interactions play a key role in the escape of light ions from its ionosphere. These ions begin life as neutrals. The solar wind's interaction with the atmosphere and ionosphere of Mars is probably relatively stronger than its more indirect interaction with earth's. The escape of Martian ions to the solar wind is not well understood; knowledge of it could be a factor in calculations of the evolution of the Martian atmosphere, and thus ultimately may relate to the question of whether life could ever have existed on Mars. Planning for future geophysical exploration of the Martian interior is also impacted by our lack of information on the solar-wind interaction. A highly desirable experiment is to use the magnetic field due to the ionospheric and magnetospheric current systems to sound the conductivity profile of the upper mantle as we do here on earth. However, at present we do not know the strength of these current systems nor their dependence on solar-wind conditions.

7.2.2.6 Dynamo Theory and Comparative Planetary Magnetospheres

The dynamo theory of planetary magnetism is a fundamental hydromagnetic problem. Any magnetic field originating from electric currents in an electrically conducting planetary core must decay unless it is maintained by electromotive forces. The ohmic decay times of planetary magnetic fields vary from 10^4 years (Mercury, earth) to 10^7 years (Jupiter). Since these times are short compared with the age of the solar system, and since the mean strength of geomagnetism has not changed much throughout geologic history, a process that provides the electromotive forces to sustain the currents in planetary cores is required. The dynamo process is generally regarded as the only possible explanation for the origin of planetary magnetism. Motions of an electrically conducting fluid in a magnetic field induce currents by electromagnetic induction. When the magnetic field produced by the induced currents matches the initial magnetic field in form and strength, a self-excited dynamo can be maintained.

In past decades, theoretical attention focused on the kinematic dynamo problem, in which a given velocity field is assumed *ab initio*. Kinematic dynamo theory neglects nonlinear effects, which determine the equilibrium amplitude of the magnetic field. Also, one cannot identify the planetary dynamo mechanism using kinematic dynamo theory, since different velocity fields can generate magnetic fields that are essentially identical outside the conducting fluid core. For these reasons, attention has shifted more recently toward the full or hydromagnetic dynamo problem. Here equations of motion including the Lorentz force are considered for the velocity field in conjunction with the induction equation for the magnetic field. Because this problem is nonlinear, few solutions have been obtained. The occurrence of nonlinear oscillations and field reversals and how magnetic energy is equilibrated are still poorly understood.

Future progress in planetary dynamo theory will require development of realistic computational models for dynamos in fluid spheres as well as analytical studies of the basic nonlinear properties of hydromagnetic dynamos. Since connection is the most likely source of motion in all planets, a general theory of planetary magnetism appears feasible. *In situ detection of the magnetic fields of each planetary body provides essential information on the dynamo process, one of the most fundamental of all hydromagnetic problems.*

The theory of comparative magnetospheres is the framework into which all planetary magnetospheres should eventually be placed. Its aim is to deduce the characteristics of each hydromagnetic envelope from its parent planet's most basic parameters—its magnetic field and rotation rate—and of its plasma sources. We have identified at least four possible plasma sources: the solar wind; the planetary ionosphere; the surfaces, atmospheres, and plasma and neutral rings of its satellites; and the interstellar medium. Each major planetary body in the solar system occupies a different portion of the spectrum of magnetospheres. The moon has no dynamo magnetic field, Mercury has no ionosphere, Venus's ionospheric interaction with the solar wind may dominate; Mars's may have a mixed magnetospheric, direct ionospheric interaction; earth has a strong magnetospheric interaction but rotates slowly; both Jupiter and Saturn are rapid rotators, but their satellite plasma sources, Io and possibly Titan, may lie in different regions of their magnetospheres; Uranus's magnetosphere may be pole-on to the solar wind; and Neptune's magnetosphere may be strongly affected by interstellar matter. Thus, the solar system has a variety of magnetospheres sufficient to make their comparative study fruitful.

A secure comparative theory of planetary magnetospheres could be extended beyond the solar system or to situations that do not now exist. The earth's paleomagnetosphere has already been calculated from the remnant magnetism in the earth's crust. These studies seek to estimate such things as the increased energetic particle flux on the earth's atmosphere and the escape of ionospheric plasma during geomagnetic-field reversals. Since field reversals appear frequently in the geological record, these studies are necessary to evaluate the long-term effect of the solar wind on the earth. The solar wind was probably more powerful in the distant past than it is today. A reliable theory of comparative magnetospheres could describe the evolution of planetary magnetospheres over the history of the solar system. Such work could be important for atmospheric evolution as well. The comparative study of planetary magnetospheres may well be extended to astrophysical magnetospheres in the future. The events of the past five years now make it a new theoretical and experimental objective of solar-system magnetohydrodynamics.[17] Comparison highlights each magnetosphere and puts that of our home, earth, in context.

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[17] Orbital exploration of the hydromagnetic envelopes of Mercury, Jupiter, Mars, and Venus and reconnaissance flybys of Saturn and Uranus would put comparative planetary magnetospheres on a solid experimental foundation, provided they determine the differences and similarities between the physical processes operative at each planet.

7.3 GENERAL STATUS OF SOLAR-SYSTEM MAGNETOHYDRODYNAMICS

Spacecraft studies of the solar system pass through three evolutionary phases as they develop: reconnaissance, exploration, and problem solving. Reconnaissance—the first penetration of a given volume of space by an instrumented spacecraft—has discovery as its objective. Reconnaissance is followed by exploration, whose aim is complete phenomenological description and the identification of important physical mechanisms. With phenomenology clear and physical mechanisms identified, problem solving begins. Here, research focuses on quantitative evaluation of physical mechanisms and their linkage one to another in comprehensive quantitative models.[18]

The magnetospheres of Saturn, Uranus, and Neptune and the interaction of the solar wind with Pluto, comets, and the heliopause still await their first reconnaissance. Exploration of the magnetospheres of Jupiter and Mercury and of the interaction of the solar wind with Mars and Venus is at an early phase. The hydromagnetic envelopes of these planets should be explored using orbiters, in order to achieve an adequate phenomenological description.[19] Not until the similarities and differences between the physical processes occurring at these planets and at earth are understood can their exploration be considered complete.

The solar wind and terrestrial magnetosphere, whose study is generally thought to have passed into the problem-solving phase, have been incompletely explored. While there have been two reconnaissance penetrations of it by Pioneer spacecraft, the geomagnetic tail beyond 100 R_e and the earth's wake in the solar wind have not been explored. *A study of a deep geomagnetic tail and wake mission* should be carried out soon because of the potential great importance. The solar wind has been explored spatially to 16 A.U., 5–10 percent of the distance to the heliopause, and then only within ±7° of the ecliptic plane. *Exploration of the solar wind will not be complete*

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[18] We imply no value judgment by listing reconnaissance, exploration, and problem-solving in temporal order; they are labels of a given subject's stage of scientific development.

[19] Jupiter's magnetosphere is so time variable as to render flyby data ambiguous (as is most likely the case for Saturn and Uranus, too). Flybys of Mercury are too short to accumulate data on its magnetosphere's response to variable solar-wind conditions. Orbiters are needed to sort out the intrinsic from the induced magnetic field at Mars and Venus.

until its third dimension has been investigated out of the ecliptic plane. In addition, the solar wind has not been studied sufficiently closely to the sun that the coronal processes driving it can be unambiguously identified. *The dependence of the solar wind and its interaction with the planets and cosmic rays on the solar cycle has been incompletely explored.* These processes have been studied with modern instrumentation for little more than one solar cycle. Not all solar cycles are alike.[20] Our understanding of the solar wind and its interaction with all the planets may be biased by the historical accident of when space exploration began.[21] The sun and heliosphere must be studied with modern techniques for several solar cycles before their exploration can be deemed reasonably complete.

In earlier sections, we discussed scientific problems that have emerged from recent exploratory research in the solar wind and terrestrial magnetosphere. The precision with which these problems can be posed indicates that much of solar-wind and terrestrial magnetospheric physics has passed or is about to pass into an advanced problem-solving phase. *However, the uneven exploration of the solar wind and earth's magnetosphere limits our capacity to solve these problems.*

Until scientific problems could be clearly stated, problem-oriented missions could not be designed. Only now will one such mission be flown. The International Sun-Earth Explorer (ISEE) mission campaign, commenced in Fall 1977, comprises a closely spaced "mother–daughter" pair of spacecraft in elliptical earth orbit and

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[20] Historical research has shown that solar activity can be depressed for decades. Sunspots, first observed telescopically by Galileo in 1612 continued to be observed until 1645. They were absent between 1645 and 1715. There is evidence for increased ^{14}C production in the earth's atmosphere, consistent with solar activity, during this 70-year period. There is weaker ^{14}C evidence for depressed activity in the fifteenth century A.D. and in the fourth, seventh, and fourteenth centuries B.C. Interestingly enough, these centuries had abnormally cold climate. Recently, overall solar-cycle activity passed through an extremely strong maximum in 1958, followed by a much weaker maximum in 1968, and now, in 1977, shows every evidence of continuing its decline. Even though in this century solar cycles have tended to recur approximately every 10 years, the latest appears to have taken 13 years to begin. This behavior has been noted before, preceding a series of weak solar cycles.

[21] Our lack of perspective could also have operational implications. Since we are in a period of quiet solar activity, the planets' upper atmospheres are relatively cold. In order to estimate the atmospheric drag on planned orbiting spacecraft, we must know how their atmospheres depend on solar activity and then project solar activity forward in time.

one in the solar wind upstream of the earth's magnetosphere. Not only will ISEE's scientific output be qualitatively new, but the operational experience gained with ISEE will be essential to planning future missions oriented around other physical problems. The International Magnetospheric Study (IMS), of which ISEE is a part, will coordinate ground-based and spacecraft experiments on the earth's magnetosphere, ionosphere, and upper atmosphere and the solar wind on a global scale. The IMS is one institutional response to the increasing problem orientation of research in these subjects.

What criteria for success shall we use in problem-oriented research? First and foremost is agreement between theory and experiment, which applies to scientific research in all circumstances. Evidence for success comes when results in one area can be confidently generalized to another.[22] Thus, on this last basis, many problems in solar-system magnetohydrodynamics are well defined and even have partial answers, although they have not yet been solved.[23]

7.4 RECOMMENDATIONS

7.4.1 Rationales for Continued Research in Solar-System Magnetohydrodynamics

Three principal rationales for intensive study of solar-system magnetohydrodynamics are its intrinsic interest, its value to other scientific disciplines, and its present and future impact on man and his technology. First and foremost is intrinsic interest, since no scientific discipline can be vigorous without it: the entire solar system is immersed in a hot flowing plasma that interacts uniquely and significantly with each of the planets and with cosmic rays, comets, and

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[22] The use of basic solar-wind theory in many astrophysical contexts is one example. Understanding of the terrestrial radiation belts, while incomplete, was sufficiently firm that it could be applied immediately to the Jovian radiation belts. In fact, our understanding of Jupiter's magnetosphere after four weeks of flyby data is equivalent to that obtained for earth only after a few years. One can therefore expect the same compression of progress in the explorations of the solar wind's third dimension and of other planetary magnetospheres. All in all, a case can be made that the problem-oriented subjects pace the advance of those in earlier stages of development.

[23] For example, because we do not understand terrestrial substorms quantitatively, we do not understand them at Mercury, and we have no idea of their nature, if they occur, at Jupiter. Nor can we state precisely the similarities and differences between planetary substorms and solar flares.

the interstellar medium. We perceive a deepening and increasingly unified interest in all these problems, which have attracted a large international community to their study.

The solar-system magnetohydrodynamics community, while pursuing its disciplinary interests, has made and will continue to make important contributions to other sciences. The heliosphere is the primary laboratory in which hydromagnetic flows and their interactions can be studied experimentally.[24] Only in the solar wind has fully developed nonlinear hydromagnetic turbulence been studied experimentally. Heliosphere experiments have motivated creation of an extensive body of hydromagnetic theory, which has been an important source of analogy for astrophysics, together with the assurance based on experience that these analogies are credible. That pulsars, x-ray sources, and radio galaxies are thought to have magnetospheres attests to this. Astrophysical research on stellar and galactic winds is a direct outgrowth of solar-wind research. Solar-system magnetohydrodynamics provides important information to planetary atmospheric physics. Hydromagnetic phenomena on the sun and in the heliosphere have a significant impact on man and his technology. The many users of terrestrial geomagnetic activity indices serve to emphasize the considerable practical interest of diverse origins in the interactions of the solar wind with the earth's magnetosphere, ionosphere, and atmosphere.[25] Recently, important unresolved questions have been raised concerning possible relations between long-term changes in the sun's hydromagnetic properties and terrestrial climate and between short-term solar-wind hydromagnetic activity and terrestrial weather. These subjects are properly controversial, since they are in a nascent stage of development. Without taking sides, we believe that these questions are sufficiently important that they deserve a concerted effort to answer them. Since the physical mechanism responsible for possible hydromagnetic couplings to terrestrial weather and climate are unknown, we cannot identify spacecraft missions or design a program that would provide credible answers. These questions do argue that the entire discipline of solar-system plasma physics, including solar-system magnetohydrodynamics, should be strengthened.

7.4.2 General Recommendation

We believe the above rationales make a vigorous national effort in research relating to the hydromagnetic and plasma phenomena on the sun and in the heliosphere consistent with NASA's charter, defined by the National Aeronautics and Space Act of 1958, which in its Declaration of Policy and Purpose lists eight major objectives including the expansion of human knowledge of phenomena in the atmosphere and in space and the establishment of long-range studies of the potential benefits to be gained from the opportunities for, and the problems involved in, the utilization of aeronautical and space activities for peaceful and scientific purposes.

Thus, *solar-system magnetohydrodynamics, and more generally, solar-system plasma physics, will deserve a high priority within the United States overall space research effort throughout the coming decade.*

7.4.3 Spacecraft Missions

Vigorous investigation of the solar wind and its interactions with the planets, comets, and cosmic rays throughout the coming solar cycle will continue to require new reconnaissance and exploratory mission starts and increased emphasis on problem-oriented missions and mission campaigns. We have listed some possible scientific objectives for such missions in Sections 7.2 and 7.3.

While scientific programs pass relatively easily from reconnaissance to exploration, their entry into the problem-solving phase is a significant transition not automatically accomplished. Individual spacecraft must be carefully instrumented to provide synoptic data relevant to theory.

In some cases, closely spaced spacecraft are now needed to provide the spatially resolved data crucial to quantitative evaluation of physical mechanisms.[26] The concurrent need to construct global models

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[24] Ground laboratory experiments have played a smaller role in extending our understanding of hydromagnetics. This will probably continue to be the case. By contrast, laboratory experiments have made extremely important contributions to the understanding of microscopic kinetic plasma processes.

[25] See the discussion of the technological impact of earth magnetospheric research in Volume 2 by L. J. Lanzerotti.

[26] This is because plasma dissipation often occurs in thin layers. Examples are the earth's magnetopause, tail plasma sheet, and auroral-zone field-aligned current region. In addition, the study of hydromagnetic structures and turbulence in the solar wind requires spatially resolved data. These problems all study the coupling of microscopic plasma dissipation and macroscopic hydromagnetic phenomena.

creates the need for close coordination between widely spaced independent spacecraft missions and, for the terrestrial magnetosphere, ground-based observations.[27] There is increased reliance on theory for the design and interpretation of spacecraft experiments and for long-range planning in the problem-oriented phase. Here, lack of adequate theory can inhibit experimental progress.[28] Finally, when comprehensive phenomenological understanding has been achieved, and when quantitative theoretical modeling has begun, it makes sense to undertake active experiments.[29] We foresee that each of the considerations above will become increasingly important to research in solar-system plasma physics.

The above discussion suggests that planning be guided by three principles:

1. *The research program of solar-system plasma physics, including solar physics and astronomy, solar-wind physics, and terrestrial and planetary magnetospheric and ionospheric physics, should be planned together.*[30]

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[27] For example, it is highly desirable to study the earth's magnetosphere while simultaneously monitoring the solar wind and the auroral atmosphere, ionosphere, and light emissions.

[28] There are several subjects in which inadequate theoretical development is as serious an impediment to progress as current experimental shortcomings. Notable examples are the inadequacy of current hydromagnetic turbulence and cosmic-ray scattering theories in the solar wind, insufficiently quantitative theories of magnetopause transport processes, insufficiently quantitative understanding of AIM electrodynamic couplings, and the absence of comprehensive conceptual models of Jupiter's outer magnetosphere sufficient to account for its gross time dependences.

[29] The studies of the earth's atmosphere–ionosphere–magnetosphere interactions are now ready to benefit from the opportunities for active experimentation provided by the Space Shuttle. Any time a new experimental technology is introduced one can reasonably hope for new information of a qualitatively different order. (However, we caution against active experimentation solely for its own sake; one wants to avoid studying spacecraft-unique active perturbations.)

[30] Other fields, such as planetology, have planned their futures, but solar-system plasma physics has not done so well as it should. This panel does not have the mandate for such a study, a logical extension of its work. A plan for the post-1980 shuttle era in earth's magnetospheric physics is urgently needed. The balance between new active experiments and continued study on the important problems already posed has not been defined. A study addressing the issue might allay the anxieties of some earth magnetospheric physicists. This current study has already taken time and energy that could have profitably been devoted to this and similar questions.

2. *Since theory and new technology are rapidly evolving, planning and its implementation should be regularly updated by SSB review of ongoing missions, theory, experiment, and new technology.*[31]

3. *The scientific problem-oriented mode of research should be strengthened in all branches of solar-system plasma physics and particularly in solar-wind and terrestrial magnetospheric physics.*

7.4.4 Data Analysis and Theory

Science progresses primarily by interaction of theory with experiment. Disagreement between them always should and often has provoked a high level of theoretical and experimental activity to resolve it. We define closure to be the activity of seeking agreement between theory and experiment. Closure forces intellectual rigor; theorists are forced to produce detailed models and predictions, experimentalists to collect and reduce theoretically significant data. When closure is compromised, theorists produce qualitative theories that experimentalists feel no need to test. The demand for closure becomes increasingly insistent as a subject develops. Where circumstance, inertia, outdated priorities, and lack of initiative or funds inhibit closure, a wasteful unnecessary diminution of scientific vitality soon follows. The most cost-effective way to improve closure is to increase data reduction and theory.

The optimum development of solar-system magnetohydrodynamics has long needed, requires now, and will continue to require a significantly larger expenditure on data analysis and theory than at present.[32] The fractional funding devoted to data analysis and theory has not kept pace with, and consequently has slowed, the development of solar-system magnetohydrodynamics.

7.4.4.1 Data Analysis

The typical mission lifetime is now often less than the time interval separating missions of significance to a given physical problem. The

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[31] We believe that the impact of new technology on the future conduct of this subject is not well understood by its practitioners. The revolution in our capabilities to come with the Space Shuttle is at best dimly perceived. Information technology is evolving exceedingly rapidly at present. The quickening space activities associated with atmospheric physics and meteorology, seismology, and oceanography among others, may also provide new modes of research in terrestrial magnetospheric physics. These examples suggest that we may soon find new ways of addressing our current problems and find new problems suddenly accessible to attack.

[32] We believe that this remark applies to all of solar-system plasma physics.

"dead" time between missions is increasing. Experimentalists, having "finished" one investigation, turn to different subjects and experiments and usually divide their attention between disparate technical and scientific problems. From the problem-oriented point of view, this leads to an unfortunate "hysteresis," with bursts of activity followed by periods of lassitude during which people change direction and interests and previously acquired understanding can lose its immediacy. Our scientific vitality now depends increasingly on what we do between mission. *Continued analysis of data is essential.* Much of the mission operations phase is now spent putting complex data in meaningful form, and an intellectual interchange between spacecraft experimentalists and the wider scientific community can only develop afterward. Increased data analysis would enhance the critical confrontation of theory and experiment, so fundamental to the scientific method.

Data analysis is a critical nutrient for scientific growth. Although data analysis is a small fraction of the overall budget for solar-system magnetohydrodynamics, its incremental value exceeds its incremental cost.

7.4.4.2 Theory

The current level of theoretical effort is inadequate throughout solar-system plasma physics. The degree of inadequacy varies from subject to subject, but inadequacy exists across the board. Its level of theoretical effort is inadequate relative to other neighboring branches of physics,[33] relative to the sophisticated data currently being collected, and is insufficient for its scientific planning, as well as increasing its interaction with other scientific disciplines. Several unresolved theoretical problems impede its scientific progress as effectively as experimental shortcomings. Its present theoretical community is

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[33] The controlled thermonuclear research (CTR) program has a fractionally larger theoretical effort than does solar-system plasma physics. CTR devotes teams of theoreticians to its significant problems; everything that can be done is done quickly, and as a result many CTR problems are resolved quickly and decisively. By contrast, while there are many intelligent theoretical papers in solar-system plasma physics, many problems remain still unresolved after years of consideration. Yet solar-system plasma theory is inherently no more difficult than CTR theory, since both are branches of the same subject—plasma physics. The above shortcoming we interpret as due to insufficient group efforts and an unhealthy lack of competition.

probably insufficient to cope with foreseeable future demands placed on it.[34]

Theory, like data analysis, is another area whose incremental value currently exceeds its incremental cost. Yet money alone will not suffice to attract strong theoreticians to solar-system plasma physics. There should be a clearly visible long-range commitment to theory in all phases of the field. Fundamental theory, which creates new concepts based on past theoretical and experimental advances, must be given its just priority. Folding theory into data analysis should have a consistently high priority. Finally, theoreticians in solar-system plasma physics should have access to those theoretical tools that they could reasonably expect in other disciplines.[35]

Theory has a technology, just as does experiment. Many hydromagnetic problems cannot be solved analytically, except in special cases so idealized that detailed comparison with experiment is extremely difficult. Other subjects faced with nonlinear flow problems, such as atmospheric physics, aerodynamics, and geophysical fluid dynamics, regularly use numerical modeling; solar-system plasma physics does not. The theoretical technology applied to laboratory plasmas has progressed well beyond that applied to solar-system plasmas. Kinetic plasma simulation numerically following many individual charged particles has proven a powerful stimulus to the theory of nonlinear microscopic plasma processes. Theoretical technology has not advanced nearly so much as experiment in solar-system plasma physics, nor has it kept pace with theoretical technology in other subjects. Ten years ago, this lack was not an impediment to closure with experiment; now it is.

We recommend initiation of a program of numerical simulation and modeling devoted to solar-system plasma physics, to ensure that it will be equipped to meet the challenges of the increasingly problem-oriented research that lies ahead. Furthermore, we would

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[34] Here we present two examples among many. The Space Shuttle will permit active plasma experiments in the earth's magnetosphere; these will require extensive theory *just to determine if they are operating properly*. If there is indeed something to the complex of questions surrounding the relations between the sun and solar wind and terrestrial weather and climate, all the disciplines of solar-system plasma physics will be strained to produce a comprehensive physical model.

[35] The unavailability of these tools may be one reason why some young plasma theoreticians choose to work in such fields as CTR rather than in solar-system plasma physics.

hope to create an active theoretical atmosphere attractive to creative individuals, realizing that computing can never replace creative thought.

7.4.5 Concluding Remarks

Solar-system plasma physics has evolved from an originally concentrated exploration of the sun, the local solar wind, and the earth's magnetosphere to an integrated scientific study of plasma phenomena throughout the entire solar system. Its practitioners come from many different intellectual and institutional backgrounds, as the diversity of the scientific journals in which they publish illustrates. Yet the growing use of hydromagnetic and plasma concepts to define many physical problems in the solar system bespeaks a growing intellectual unification of solar-system plasma physics. This suggests that a stronger institutional unification will soon be called for. Like other space sciences, it is faced with reconciling an increasing sophistication and diversity of its scientific goals with a greater complexity and decreasing launch frequency of spacecraft experiments. Its ability to resolve this tension creatively has been compromised by inflation and other budgetary restraints. It should be of general concern that solar-system plasma physics continue its successful development, for it is the first of the scientific disciplines created by the United States commitment to an energetic space program to reach "adolescence"; how it grows into "maturity" will be a precedent for the other space sciences inevitably following in its path.

8

Solar-System Plasma Processes

8.1 SUMMARY

Space plasma physics seeks an understanding of the plasma processes in the solar system. Plasmas in the solar system consist of ionized particles, predominantly protons and electrons, as well as electromagnetic, electrostatic, and hydromagnetic waves. Ionized atoms, including helium, oxygen, and heavier species, are also important in some regions of space.

- Studies of plasma processes in the solar system have yielded important scientific results that have wide applicability to laboratory and astrophysical plasma conditions.
- The results of research on plasma processes in the near-earth environment have had in the past, and can be expected to continue to have in the future, important impacts on society and technology.
- Plasma processes that are of current scientific interest include ionospheric plasmas, radiation belts, plasma waves, magnetic-field-aligned currents and parallel electric fields, magnetic-field reconnection, collisionless shock waves, and solar-wind plasma kinetic processes.
- Continued advances in an understanding of solar-system plasma processes require support for the following items, with specific emphasis depending on the science subject area:
  - (a) Problem-oriented data analysis, interpretation, and theory.
  - (b) Problem-oriented new mission planning, implementation, and data analysis.
  - (c) Computer simulation and modeling capabilities.
  - (d) Laboratory plasma experiments.
  - (e) Coordinated ground-based observations.

8.2 INTRODUCTION

The solar-system plasma environment can be directly probed, providing access to plasmas in states approaching those prevailing in most of the universe. The basic physical processes operative in this environment can be studied and detailed understanding achieved. The accessibility of the solar-system plasmas to direct probing is in contrast to our study of the remainder of the physical universe, where information is available to us only via the electromagnetic and corpuscular radiation from the various astronomical objects. In addition, the study of solar-system plasmas affords opportunities to learn about regions of plasma parameter space that are inaccessible to regular laboratory experiments and to investigate plasmas that are unaffected by containment devices. In several areas, near-earth space research has made the dominant contributions to basic plasma science. Other processes are of equal importance in both space and laboratory plasmas, and the results from the two regimes aid in the advancement of research in each.

Apart from satisfying the fundamental human desire to know and understand our natural environment, the understanding of solar-system plasmas and solar–terrestrial relations can reasonably be expected to be of continued technological and economic significance. The impact of solar and geomagnetic activity on communications and power systems is well documented; the impacts on manned space stations and missions will be of more importance in the future; the influences on terrestrial weather and climate remain to be thoroughly investigated.

In 1975, NASA conducted a major internal study concerning the future directions that activities by the United States in space might take. The resulting *Outlook for Space* (NASA, Washington, D.C., 1976) defined 61 future space objectives that were divided into 12 themes (Table 6, Chapter 5, page 38). This table is reproduced here as Figure 8.1. The objectives and themes that we believe solar-system plasma studies impact upon at some stage in their investigations are left unshaded. Those objectives and themes for which plasma studies are peripheral or unimportant to their pursuit are shaded. We believe that it is clear from this table that solar-system plasma research is important for NASA-defined future space objectives, ranging from some of the most practical concerns to some of the most deep cosmological questions.

Future solar-system investigations must turn from those that emphasize exploration to those that seek deep understanding of the

EARTH ORIENTED ACTIVITIES RESPONSIVE TO BASIC HUMAN NEEDS

THEME 01 PRODUCTION AND MANAGEMENT OF FOOD AND FORESTRY RESOURCES
Objective 011 – Global Crop Production Forecasting
Objective 012 – Water Availability Forecasting
Objective 013 – Land Use and Environmental Assessment
Objective 014 – Living Marine Resource Assessment
Objective 015 – Timber Inventory
Objective 016 – Rangeland Assessment

THEME 02 PREDICTION AND PROTECTION OF THE ENVIRONMENT
Objective 021 – Large-Scale Weather Forecasting
Objective 022 – Weather Modification Experiments Support
Objective 023 – Climate Prediction
Objective 024 – Stratospheric Changes and Effects
Objective 025 – Water Quality Monitoring
Objective 026 – Global Marine Weather Forecasting

THEME 03: PROTECTION OF LIFE AND PROPERTY
Objective 031 – Local Weather and Severe Storm Forecasting
Objective 032 – Tropospheric Pollutants Monitoring
Objective 033 – Hazard Forecasting from *In-Situ* Measurements
Objective 034 – Communication-Navigation Capability
Objective 035 – Earthquake Prediction
Objective 036 – Control of Harmful Insects

THEME 04: ENERGY AND MINERAL EXPLORATION
Objective 041 – Solar-Power Stations in Space
Objective 042 – Power Relay via Satellites
Objective 043 – Hazardous Waste Disposal in Space
Objective 044 – World Geologic Atlas

THEME 05: TRANSFER OF INFORMATION
Objective 051 – Domestic Communications
Objective 052 – Intercontinental Communications
Objective 053 – Personal Communications

THEME 06: USE OF ENVIRONMENT OF SPACE FOR SCIENTIFIC AND COMMERCIAL PURPOSES
Objective 061 – Basic Physics and Chemistry
Objective 062 – Materials Science
Objective 063 – Commercial Inorganic Processing
Objective 064 – Biological Materials Research and Application
Objective 065 – Effects of Gravity on Terrestrial Life
Objective 066 – Living and Working in Space
Objective 067 – Physiology and Disease Processes

THEME 07: EARTH SCIENCE
Objective 071 – Earth's Magnetic Field
Objective 072 – Crustal Dynamics
Objective 073 – Ocean Interior and Dynamics
Objective 074 – Dynamics and Energetics of Lower Atmosphere
Objective 075 – Structure, Chemistry, and Dynamics of the Stratosphere Mesosphere
Objective 076 – Ionosphere-Magnetosphere Coupling

EXTRATERRESTRIAL ACTIVITIES RESPONSIVE TO INTELLECTUAL HUMAN NEEDS

THEME 08: THE NATURE OF THE UNIVERSE
Objective 081 – How did the Universe Begin?
Objective 082 – How do Galaxies Form and Evolve?
Objective 083 – What are Quasars?
Objective 084 – Will the Universe Expand Forever?
Objective 085 – What is the Nature of Gravity?

THEME 09: THE ORIGINS AND FATE OF MATTER
Objective 091 – What is the Nature of Stellar Explosions?
Objective 092 – What is the Nature of Black Holes?
Objective 093 – Where and How Were Elements Formed?
Objective 094 – What is the Nature of Cosmic Rays?

THEME 10: THE LIFE CYCLE OF THE SUN AND STARS
Objective 101 – What are the Composition and Dynamics of Interstellar Matter?
Objective 102 – Why and How Does Interstellar Dust Condense into Stars and Planets?
Objective 103 – What are the Nature and Cause of Solar Activity?
Objective 104 – Corona and Interplanetary Plasma
Objective 105 – What is the Ultimate Fate of the Sun?

THEME 11: EVOLUTION OF THE SOLAR SYSTEM
Objective 111 – What Process Occurred During Formation of the Solar System?
Objective 112 – How do Planets, Large Satellites, and Their Atmospheres Evolve?
Objective 113 – How Can Atmospheric Dynamics be Quantified?
Objective 114 – What are the Origin and History of Magnetic Fields?

THEME 12: ORIGINS AND FUTURE OF LIFE
Objective 121 – How Did Life on Earth Originate?
Objective 122 – Is There Extraterrestrial Life in the Solar System?
Objective 123 – What Organic Chemistry Occurs in the the Universe?
Objective 124 – Do Other Stars Have Planets?
Objective 125 – Can We Detect Extraterrestrial Intelligent Life?

FIGURE 8.1 Future space objectives–1980 to 2000.

physical processes governing the natural environment. This evolution, which will inevitably occur in the future in all disciplines of space science, involves a change in emphasis from a purely mission-defined mode to a science problem-defined mode of research. Section 8.3 contains summary descriptions of recent advances and future directions for research in several scientific problem areas in space plasma physics. Section 8.4 discusses some areas of contemporary practical importance of the research for society and the technology being implemented by society. In Section 8.5 we discuss in more detail our rationales for recommending science problem-defined missions, adequate data analysis, and theoretical support.

8.3 STATUS OF SCIENTIFIC TOPICS

A number of specific subjects were selected for review to illustrate the diversity of plasma-physics problems associated with solar-system investigations. These topics were selected for their high current interest as well as for their expected scientific importance in the future. Most of these subjects are concerned with the earth's ionosphere and magnetosphere, principally because this region of space has been most accessible to investigation. However, many of the concepts developed can be applied equally well to other planetary magnetospheres. The summaries define the subjects, outline some of their major recent advances, and briefly discuss present and future research directions, goals, and strategies. Much more extensive discussions are contained in the individual papers to be published in Volume 2.

8.3.1 Aspects of Ionospheric Physics

The ionosphere is a portion of the earth's upper atmosphere. It has been studied extensively since its discovery in 1925, with a view toward understanding its photochemistry, dynamics, and interactions with both the neutral atmosphere and the magnetosphere. The ionosphere is also a naturally occurring plasma in which a number of processes of fundamental plasma importance have been observed and can be conveniently studied. For example, there are known to be several plasma instabilities that can generate regions of fully developed plasma turbulence, which can persist for times ranging from minutes to hours in a reasonably stationary state. The ionosphere thus provides an excellent arena in which to study the nonlinear

saturation mechanisms of such turbulence and the cascade of energy from one scale size to another. Instabilities that have been studied extensively in recent years are encountered at altitudes of about 100 km (the E region) at equatorial and auroral latitudes and at roughly 250 km and above (the F region) at equatorial latitudes.

The E-region instabilities are driven by electron density gradients, strong electric currents, or both. The linear theory for the equatorial case is now quite well understood, and the importance of both of the driving forces has been verified. The auroral case is more complicated, and the ambient conditions more variable and difficult to measure; hence it is less well understood. There are many similarities to the equatorial E-region case, however, and progress is being made.

Much headway also has been made recently in understanding the equatorial F-region instabilities, the effects of which were first noted over 40 years ago. The basic mechanism in this case appears to be the gravitational instability of a heavy fluid supported by a lighter one (the Rayleigh-Taylor instability). The instability first appears on the steep underside of the nighttime equatorial F layer. The nonlinear development of this instability causes "bubbles" to rise through the denser F region above the altitude, which first becomes unstable, leading to the subsequent generation of unstable waves in regions that were initially gravitationally stable.

The experimental and theoretical efforts on instabilities in the equatorial E and F regions are now being concentrated on studies of the nonlinear processes. While the analytic work has thus far led to only limited success, computer simulations have begun to yield encouraging results. In the simulations, the radar echoes from the equatorial E region have been reproduced under certain specific conditions, as have the "bubbles" rising through the equatorial F region. These simulations represent a significant step forward in the understanding of the instability growth and saturation mechanisms. Once the natural phenomena have been adequately simulated by a computer code, the physical processes can be "probed" in great detail with noninterfering numerical diagnostics–a situation not possible with the real phenomena. The computer "experiments" serve to guide new analytic or semianalytic theories and allow important associated physical effects (such as anomalous resistivity and enhanced diffusion) to be accurately modeled.

All plasmas, including stable ionosphere plasmas, contain random thermal density fluctuations. Weak radar scattering from such ionospheric plasmas is an area of research that is of interest to a wide audience. The relevant theory, which involves only linear kinetic processes, has been developed in great detail in recent years, with the result that such "incoherent" scatter is now by far the most powerful tool for ground-based probing of the ionosphere. The technique is also employed in the probing of laboratory plasmas. In the ionospheric case, especially, the theoretical assumptions are entirely valid and the complete quantitative agreement between theory and experiment has provided a very detailed verification of linear kinetic plasma theory.

Present incoherent-scatter research involves extending the theory to include scattering from various non-Maxwellian velocity distributions (a reasonably straightforward procedure) and exploiting the technique observationally to study many aspects of the behavior of the ionosphere and, indirectly, the neutral atmosphere, for which the ionized particles often act as effective tracers.

It seems realistic to expect that these two relatively "clean" nonlinear plasma problems will be solved in the reasonably near future, at least in the equatorial regions. Toward this end, numerical and analytic theoretical work is continuing, and further radar and *in situ* probing of the natural instabilities is planned. Much further work, observational as well as theoretical, will be needed at high latitudes in the auroral regions.

Further support of ionospheric plasma research should encourage a balanced program consisting of both ground-based and orbital measurements. More comprehensive data on the physical change in the unstable regions are needed, and these data can best be provided by a comprehensive and coordinated program that utilizes simultaneous satellite, rocket, and radar measurements. Some radar facilities, now contributing in major ways to studies of ionospheric plasma instabilities, are experiencing financial difficulties. These facilities are vital for coordinated studies, and continued support would result in significant scientific returns. A continued balanced program of theoretical work (both numerical and analytical) is required to obtain optimum return from the observations.

8.3.2 Radiation Belts

Among the planetary bodies in our solar system, earth and Jupiter have been long known to possess intrinsic magnetic fields of significant strengths. It is suspected that Saturn and Uranus may also have significant fields. Both Mercury and Mars have been found to have weak planetary magnetic fields. Charged particles, such as electrons, protons, and heavier ions, can, under appropriate conditions on the particle kinetic energies, become trapped in a planetary dipole field. The particles execute motions defined by three adiabatic invariants; these three motions—cyclotron, bounce, and drift—are illustrated schematically in Figure 8.2. For systems such as the earth and Jupiter, which are subjected to external fluctuating processes, the adiabatic invariants can be violated so that the trapped-particle populations can vary dynamically. The goal of radiation-belt physics is to understand the dynamics of the trapped-particle population.

The theoretical possibility of trapped radiation belts around magnetized planets was recognized and discussed by S. F. Singer before the spacecraft era began. Experimental verification of the existence of the earth's trapped charged particles—the Van Allen belts—was the first major discovery by earth-orbiting satellites. This radiation consists of energetic electrons (from about 1 keV to about 100 MeV) and ions (in approximately the same energy range) trapped on geomagnetic-field lines, which cross the magnetic equator at geocentric distances ranging from about 1.1 to 10 R_e.

The purpose of modern radiation-belt physics is to identify and quantitatively evaluate all the important source, loss, and transport processes that operate on these magnetically confined charged particles. In this manner, an explanation and understanding of both the

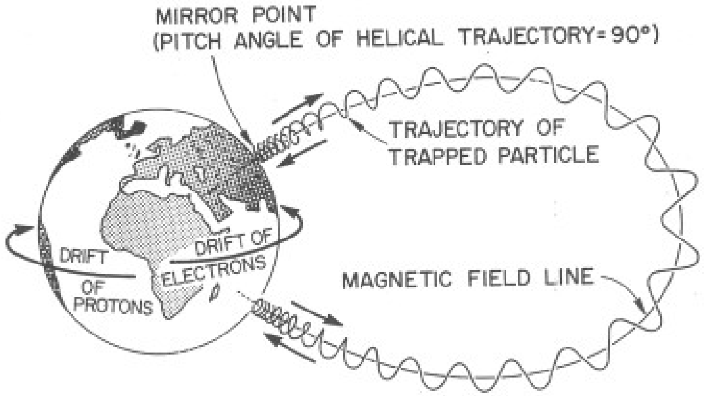

FIGURE 8.2 Motion of a charged particle in a planetary dipole magnetic field.

long-term structure and the temporal variations of radiation belts can be derived.

This understanding has been an important motivating factor for unmanned exploratory missions in the past because of the need to develop accurate radiation hazard models for use in predicting radiation dosage levels for both manned missions and for electronic components on all missions. Understanding of the earth's radiation belts prior to the launch of the two Pioneer missions to Jupiter was used as the basis for predictive theoretical modeling of the Jovian radiation belts. The models proved invaluable in providing design criteria for the required radiation hardness of spacecraft components and systems.

Significant qualitative and quantitative understanding of the structure of the earth's radiation-belt electrons (energy $\geqslant 30$ keV) and ions (energy $\geqslant 100$ keV) has now been achieved in the region below about 5 R_e for periods of relatively low geomagnetic activity. The dominant plasma processes, including macroscopic radial motions, losses, and energy-transfer processes, affecting these particles appear to have been identified and evaluated in large part. However, there remain gaps of significant proportions in our knowledge that can only be filled by properly planned future exploration and research.

For example, comprehensive energy spectra and equatorial pitch-angle distributions for electrons and ions are still needed in the entire magnetosphere region out to ~10 R_e. Major changes occur in the earth's radiation belt populations during and after significant geomagnetic disturbances, such as magnetic storms and substorms. Comprehensive analyses of temporal variations during these times is still required.

Radiation-belt variations have been qualitatively correlated with electromagnetic disturbances at frequencies from <1 Hz up to the kHz range. Such plasma waves can violate the adiabatic invariants of the particle motion and cause losses or gross changes of the trapped populations. Coordinated electric- and magnetic-field measurements out to ~10 R_e are still required to understand radiation-belt dynamics fully. Of special interest are measurements in the range from d.c. to $\sim 10^{-2}$ Hz, since this range affects the radial transport of trapped particles.

It is now known that wave transmissions from ground antennas can affect the trapped-particle populations of certain energies, producing major changes in the populations. Both deliberate transmissions from existing very-low-frequency (vlf) antennas, as well as inadvertent radiation from high harmonics of the 50-Hz and 60-Hz European and North American power grids can affect the particles. It may well be that the current notions that all radiation-belt dynamics are dominated by natural plasma waves will have to be revised as knowledge of the effects produced by man-made radiation advances. This is an exciting area of current radiation-belt research.

In summary, although present knowledge of radiation-belt physics is reasonably advanced, very significant unanswered questions remain, both at the earth as well as around the planets. The composition of the radiation-belt ions is almost completely unknown; measurements of the ions and their temporal changes should be obtained as soon as possible. Adequate wave data for quantitatively evaluating particle transport and loss processes must be obtained. A serious lack of understanding of the earth's radiation belts exists beyond ~5 R_e, where it is likely that most of the particle injections during substorms occur. The detailed distribution functions of these particles need to be measured. Continued theoretical work is needed on wave–particle interaction processes important for determining radiation-belt dynamics.

8.3.3 Plasma Waves

The term "plasma waves" characterizes all waves that are generated in a plasma or that have their wave characteristics significantly modified by the presence of a plasma. These waves may be predominantly electromagnetic (having both electric and magnetic fields produced by current fluctuations) or electrostatic (having only an electric field produced by charge fluctuations). Some plasma waves–hydromagnetic–only exist in highly ionized, magnetized media such as solar-system plasmas (recently Alfvén waves have been observed in some metals). Most waves are generated by the conversion of plasma and energetic particle kinetic energy into wave energy through a variety of wave–particle processes. In turn, these waves may interact with the particles and modify the particle populations within the plasma. Some of the regions with significant plasma-wave activity in the earth's magnetosphere are depicted in Figure 8.3.

During the past several years, the major advances in plasma-wave research have included a number of surprising discoveries as well as deeper understanding of several areas. Theories have been developed that attribute a number of the observed vlf (10 Hz to 30 kHz) emissions to amplification processes by coherent particle beam–plasma

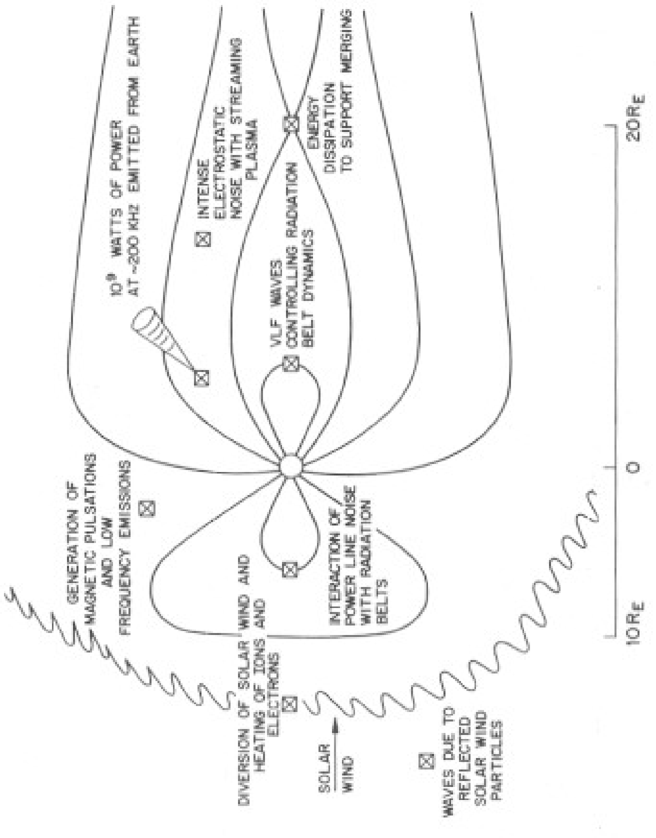

FIGURE 8.3 Schematic view of significant plasma-wave regions within the earth's magnetosphere (noon–midnight meridian profile).

wave interactions. Some of these waves are involved in the particle dynamics of the trapped radiation belts. Observationally, kilometric radiation (50–500 kHz) emanating from the earth's magnetosphere has been discovered, related to bright auroral arcs, and compared with the recently discovered hectometric (500 kHz to 2 MHz) radio bursts from Saturn and Uranus as well as to the well-known decametric (200 kHz to 40 MHz) emissions from Jupiter. It has been found that very high harmonics of the 60-Hz and 50-Hz terrestrial power systems can leak into the magnetosphere and produce electron precipitation into the ionosphere. Electrostatic noise has been detected in regions of the magnetosphere that contain hot or steaming plasma.

Current solar-system plasma-wave research seeks to understand the plasma-wave processes associated with (a) the existence and consequences of electrostatic waves; (b) the energy transfer between the magnetosphere, ionosphere, and atmosphere; (c) the energy dissipation in the bow shock and magnetotail; (d) the generation of radio bursts and emissions from the earth, Jupiter, Saturn, and Uranus; (e) the energization, diffusion, and precipitation of energetic particles in the magnetospheres of the planets; and (f) the cascading and transport of energy in the solar wind, especially related to heating of the solar corona. The electromagnetic plasma waves emitted from astrophysical sources are the only means we have for detecting and studying many of these objects. Thus, understanding of plasma-wave mechanisms in the solar system is important for understanding other astrophysical plasma processes.

For the continuation of vigorous plasma-wave research, new instrumentation needs to be developed to measure the physical characteristics of both electrostatic and electromagnetic waves. On a single satellite, three-axis antennas are required to determine the wave distribution function (frequency, wave vector, Poynting vector, and mode). Correlations of wave measurements between closely spaced spacecraft are necessary to derive wave-propagation characteristics (source direction, wave velocity, and damping or amplification factors) and to separate spatial features from temporal variations. Such instrumentation should be flown through the polar auroral magnetosphere, the plasmapause region, the magnetotail, the bow shock, and the cusp to provide measurements in the most important plasma-wave regions of the magnetosphere. Similar measurements should be made in other planetary magnetospheres and in the solar wind. Supporting laboratory experiments are necessary to identify the conditions under which the various wave modes can be generated and the mechanisms for wave–wave coupling can occur (especially between electrostatic and electromagnetic modes). Numerical plasma simulations are of particular value for following the microscopic features of wave modes and particle distribution functions as specific wave–particle interactions occur. Information from the laboratory experiments and numerical simulations must be used together with the solar-system plasma-wave observations to develop theories of these plasma-wave processes and analogous processes of astrophysical interest.

8.3.4 Magnetic-Field-Aligned Currents and Parallel Electric Field

Auroral arcs and rays are the most spectacular visual consequences of magnetic-field-aligned currents in the earth's magnetosphere. The richness of structural formations in the solar chromosphere and corona are also attributed to such currents. Measurements with magnetometers on the ground, in rockets, and in satellites have identified the major electric current systems in the terrestrial ionosphere and magnetosphere. A portion of the current system and some phenomena associated with the aurora are depicted in Figure 8.4. Observations of plasma waves and other emissions from Jupiter, Saturn, the sun, and even pulsars and radio galaxies suggest that such current systems may be of universal importance.

Measurements with particle detectors on rockets and satellites have shown that the currents just above the aurora are carried by downward precipitating electrons of keV energies. The electrons impacting the top of the atmosphere (~100 km altitude) excite the major optical emissions observed as aurora. There is abundant indirect evidence that these electrons are accelerated through a field-aligned potential drop somewhere in the altitude range of 2000 to 20,000 km above the auroral oval. This evidence includes observations of the energy and angular distributions of primary auroral particles and their spatial and temporal modulation, the occurrence of ionospheric ions accelerated to keV energies in the distance magnetosphere, and visual observations of the upward accelerations of tracer ions artificially injected into the magnetosphere. Very recent satellite measurements with an electric-field probe have confirmed the presence of field-aligned electric fields of magnitudes up to ~0.5 V/m in the altitude range 2000–8000 km.

The plasma process or processes for supporting the electric fields that lead to the particle accelerations have not been identified as yet,

principally because of the very few opportunities to fly instruments through the appropriate altitude range. A number of processes have been suggested based on theoretical considerations, numerical plasma simulations, and laboratory plasma experiments. In one such process,

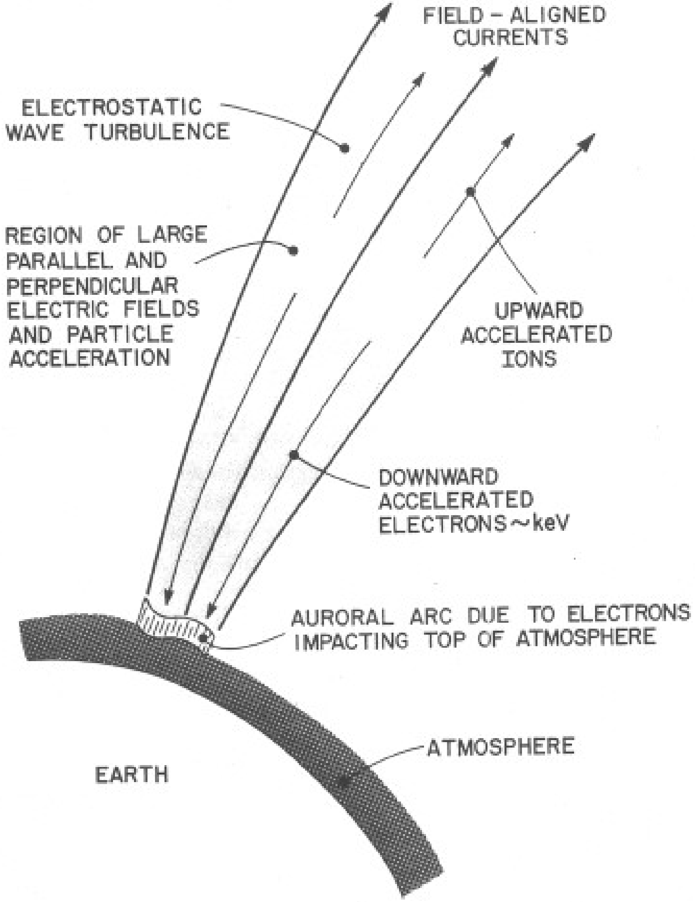

FIGURE 8.4 Pictorial representation of the field-aligned currents, parallel electric-field region, and other phenomena associated with an auroral arc.

for example, plasma-wave turbulence is produced when the particle beam current density exceeds the threshold for a plasma instability. This turbulence interacts with the particles to increase locally the effective resistivity ("anomalous resistivity") of the plasma. Some of the particles are then accelerated to high energies. Observationally, in the magnetosphere, electrostatic plasma-wave turbulence has been measured in association with field-aligned currents over a range of altitudes from the ionosphere into the cusp and into the magnetotail.

In another process, a current-driven instability can lead to a charge-separation layer ("double layer"), which produces large electric fields in a spatially limited region. The predicted electric fields from this process are consistent with the recent measurement of parallel electric fields in the 2000- to 8000-km altitude range.

The plasma processes that constitute the "battery" that drives the current systems are very poorly understood at this time, although the solar wind must be the ultimate energy source. It is expected that significant observations relevant to this problem will result from data from some future missions.

This area of near-earth plasma research needs observations by multiple spacecraft along auroral field lines—a region very poorly explored to date. Correlated measurements of electric fields, currents, energetic particles, and plasma waves are necessary to identify the responsible plasma processes. The advances to date in this science area have benefited significantly by inputs from laboratory experiments, numerical plasma simulations, and theoretical developments; these activities should be continued and even intensified. Further controlled particle and wave injection experiments will yield additional insights into the characteristics of the acceleration regions.

8.3.5 Magnetic-Field Reconnection

Most of the matter in the cosmos consists of tenuous plasma of high electrical conductivity permeated by magnetic fields. These fields may have their sources in stellar and planetary bodies, or they may be produced by electric currents flowing in the plasma itself. Plasma regions containing fields of different direction that are pushed together tend to become separated by thin layers containing intense electric currents. Such current sheets occur at the magnetopause and in the tail of planetary magnetospheres, at sector boundaries and tangential discontinuities in interplanetary space, as well as in the solar chromosphere and corona. Presumably similar current layers arise in many other cosmic systems as well. The magnetic field associated with these currents may contain large amounts of energy. The rapid conversion of this energy into plasma particle energy is thought to be the basic process occurring in violent events such as solar flares and geomagnetic substorms. Because of the large electrical conductivity of the plasma and the enormous dimensions of such current systems, resistive dissipation occurs much too slowly to account for the conversion rates observed in these events. The magnetic-field reconnection process, described below, appears to have the capability of accomplishing the conversion at a sufficiently rapid rate.

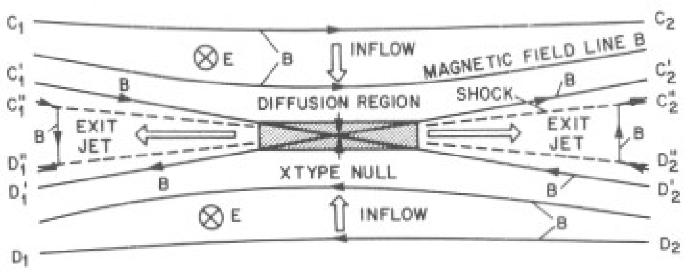

FIGURE 8.5 Schematic illustration of steady-state reconnection process, with possible magnetic-field and plasma-flow configurations.

A simple steady-state version of the reconnection process, with a possible, but not unique, magnetic-field and plasma-flow configuration is illustrated in Figure 8.5. Slow quasi-steady plasma flow occurs directed toward the current sheet, carrying with it opposing strong magnetic fields. Ejection of energized plasma takes place within the current sheet in two narrow wedge-shaped jets with vertices at an "X-type" magnetic null point. The term reconnection is used because field lines such as C_1–C_2 and D_1–D_2, which are carried with the plasma toward the current sheet, are severed and reconnected when they reach positions C_1'–C_2' and D_1'–D_2', i.e., when they touch at the null point. These field lines subsequently leave the system in the exit jets as C_1''–D_1'' and C_2''–D_2''. The plasma motion leads to a constant electric field, directed perpendicular to the figure. It is the finite resistivity of the plasma near the null point that prevents the short circuiting of this field.

The steady-state version of reconnection may occur, conceptually at least, when plasma regions are pushed together at a steady rate, as is the case at the earth's subsolar magnetopause. The nonsteady or impulsive version is relevant to flares and substorms. The magnetic-field configuration in this latter case may be similar to that shown in Figure 8.5 for the steady-state case but with the wedge angles of the exit jets increasing rapidly with time as the current sheet disintegrates and the field configuration relaxes toward its lowest-energy, current-free state. The induced electric fields in such a configuration are capable of accelerating charged particles passing near the magnetic null region to high energies.

The magnetic-field reconnection concept has been used to construct a qualitative model of the dynamic magnetosphere which has many appealing features and which has been supported in an indirect way by a multitude of observations during the last decade. However, to date, no entirely incontrovertible direct observations of the process exist either at the magnetopause or in the geomagnetic tail. Such observations are difficult to obtain for a number of practical reasons. Ideally, they require magnetic-field and plasma measurements from at least two spacecraft, located in fairly close proximity to each other and to the reconnection site at a time when reconnection does occur. It is extremely difficult to meet these conditions in the geomagnetic tail, where reconnection, if it occurs, is impulsive, and where, at present, no agreement exists concerning the expected location of the reconnection site. At the magnetopause, where reconnection at a slow rate has been thought to occur whenever the magnetosheath field has a southward component, plasma and magnetic-field data with high temporal and directional resolution are needed because the current sheet structure is very narrow. Currently available plasma data lack the requisite resolution.

Laboratory experiments in which oppositely magnetized plasmas move toward an X-type magnetic null point have shown clear evidence for reconnection both in the steady state and in the impulsive mode. Because of scaling and boundary condition considerations, it is not clear to what extent such results are directly applicable to magnetospheric and solar reconnection processes. Nevertheless, such experiments are extremely important in helping to develop our concept of the process.

The reconnection configuration shown in Figure 8.5 is a schematic one. In reality the actual geometry may be turbulent, and reconnection between fields that are not antiparallel appears entirely possible. Thus, the process may occur even in nearly force-free field configurations. Indeed, a version of the process has been observed to occur in plasma confinement devices of the tokamak type.

Theoretical studies indicate that reconnection involves a complex interaction between macroscopic and microscopic plasma processes. The overall dynamics and energy-conversion rate appear to be controlled by distant boundary conditions, by the large-scale flow and field, as well as by dissipative processes occurring in a small region surrounding the magnetic null, the so-called diffusion region. Outside this region, the dominant dynamic feature is the acceleration of plasma into the exit jets by magnetohydrodynamic slow shocks, or, more generally, by interaction with current sheets having a nonzero normal magnetic-field component. Inside the diffusion region, current-driven plasma turbulence may combine with inertial and/or collisional effects to generate an effective resistivity. If the latter is sufficiently large, energy conversion proceeds at a rate determined entirely by external boundary conditions and by external plasma dynamics; if not, reconnection is impeded, either partially or completely. Impulsive events are thought to be associated with the abrupt onset of plasma microinstabilities, and an associated increase in resistivity, in the diffusion region, during conditions conducive to large-scale conversion of free magnetic energy.

To date, most theories of reconnection have been concerned either with two-dimensional steady-state fluid models or with the onset of tearing, ion-acoustic, or other instabilities in a current sheet. Few models attempt to couple diffusion-region processes with the external flow and with large-scale dynamics in a self-consistent manner. The dynamics of impulsive events and of particle acceleration processes also have received little attention. In short, the theory of reconnection is not in a satisfactory state.

In view of the potential importance of reconnection as a universal cosmic energy conversion process and in view of the key role it plays in our present concepts of solar flares and of the dynamic magnetosphere, continued broad-based research on the plasma physics of reconnection is important in the years ahead. This effort should incorporate analytical modeling with particular emphasis on impulsive and microscopic plasma processes, laboratory experiments to elucidate the properties of the process in the resistive limit, computer simulations, magnetospheric observations using multiple spacecraft to resolve spatial and temporal effects, perhaps active magnetospheric experiments such as the use of artifically injected ions to map field lines, and continued attempts to study the relevance of the process to solar flares and other astrophysical phenomena.

8.3.6 Collisionless Shock Waves

The sudden air-pressure changes, or sonic booms, associated with the flights of supersonic jet aircraft are familiar examples of shock waves. These shocks in the earth's relatively dense, collisional atmosphere have their counterparts in the tenuous plasmas of space, where they are in fact common and have an appreciable effect on the space environment. The shock that forms in a collisionless plasma directs fluxes of gas into new directions of flow; transforms coherent, directed motion into heat; raises individual ion energies to cosmic-ray energies; and emits particle and wave energy into space far from the shock location.

The fundamental problems of the collisionless shock derive from its inherent nonlinearity, which makes closed mathematical representation difficult, and from the complexity of the plasma—a multicomponent gas of electrons and one or more ion species, pervaded by a magnetic field of sufficient energy density so that individual particle motion and wave-mode propagation and dispersion are governed by the field. In essence, the objectives of collisionless shock research are to determine (a) how nature selects the particular combinations of field and plasma parameters that fashion them; (b) how the shocks, once formed, behave; and (c) how they influence the parameters of the space environment.

Collisionless shock waves have been found on the sunward side of all five of the planets of the solar system visited thus far. In addition to the shocks at the planets, spacecraft instrumentation has measured collisionless plasma shocks traveling through the solar wind away from solar flares and ahead of plasma streams originating on the sun; the existence of such shocks has been inferred in the solar atmosphere as well as in distant parts of the universe. Particles are reflected from, and energized by, shocks. Waves are generated in the solar wind both upstream and behind them. In the case of the earth's bow shock, a portion of the energy of the downstream waves is transferred to the surface of the earth. Such an energy transference may well occur at other planets as well.

The study of natural plasma shocks in space has benefited from traditional methodology. Laboratory experiments, for example, have played an important role in defining collisionless shock phenomenology. Such laboratory shocks have been observed in oscillatory motion; upstream standing whistler waves have been observed that destabilize and are damped; some laboratory shock thickness scales have been measured.

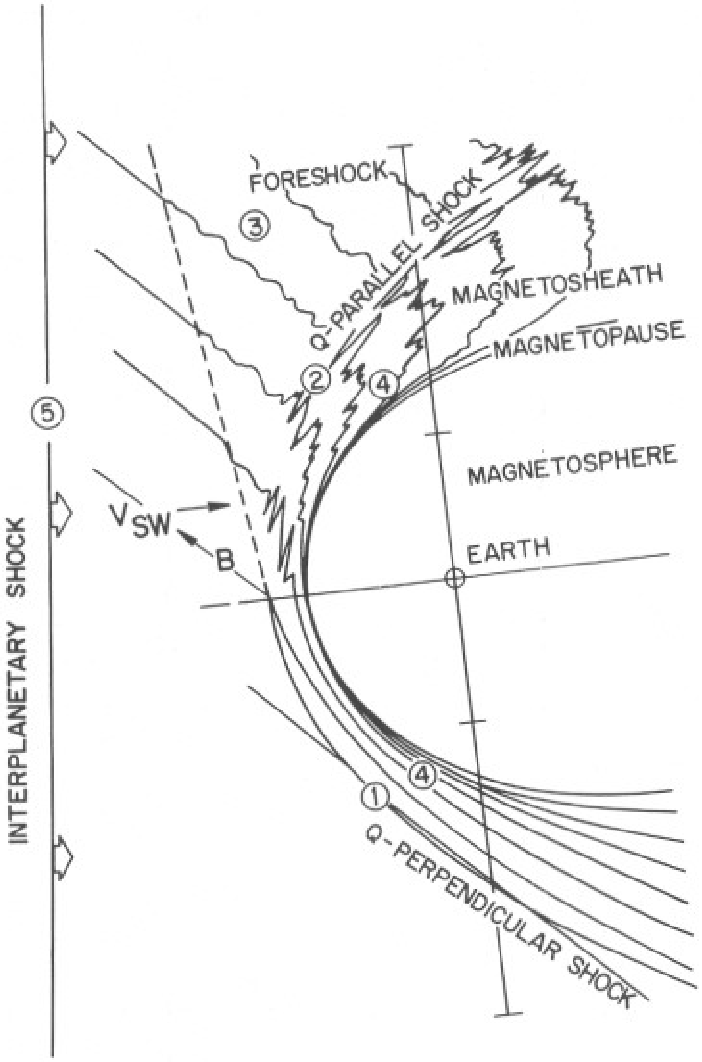

FIGURE 8.6 Ecliptic-plane, cross-section schematic view of the earth's bow-shock system with an approaching solar-wind shock. The interplanetary magnetic field lies in the plane of the paper. The numbers refer to physical regimes discussed in Section 8.3.6.

Numerical simulation studies of collisionless shocks have also been helpful. They have demonstrated counterstreaming ions, wave formations, and model profiles of field and particle changes within certain specialized shock structures. Conversely, natural collisionless shocks have revealed patterns, structures, and details unknown or inaccessible to terrestrial techniques.

At present, the qualitative description of the macrophenomenology of the collisionless shock at the earth is, if not complete, at least well in hand. Most of the problems of collisionless shock physics that lie ahead involve the quantitative determination of the microscopic processes that determine the structural form of the shock in different states of the solar wind. Figure 8.6 is an ecliptic-plane cross section of the earth's bow-shock system for a nominal interplanetary magnetic-field orientation in the plane of the paper, with an approaching solar-wind shock also shown edge on. The distinction between shocks propagating with their normals more than about 45° from the ambient magnetic field (quasi-perpendicular) and within 45° of the ambient field (quasi-parallel), the coexistence of both structures in a single, curved bow shock, and the extension of the quasi-parallel structure upstream to form the foreshock are major properties defined by satellite observations. The circled numbers in the figure designate the physical regimes in which outstanding issues remain to be investigated according to the present view. These issues are as follows:

8.3.6.1 Ion Heating

One of the most important discoveries will be the identification of the instability or process that acts in strong, quasi-perpendicular (q-perpendicular) shocks to produce ion heating, greater than the electron heating, to temperatures several times that of the unshocked ions. The promising candidates are ion-acoustic and lower-hybrid instabilities and macroscopic gyration.

8.3.6.2 Pulsation Structure

The wave modes and particle distributions that compose quasi-parallel (q-parallel) shocks and their means of interaction must be determined. An explanation has not been found for why protons in the earth's shock are heated to certain consistently repeated multiples of their original energy before appearing in the foreshock.

8.3.6.3 Foreshock Structure

The composition and structure of the foreshock and its role as a part of both transient and steady-state q-parallel shock processes has yet to be established.

8.3.6.4 Magnetosheath Structure

The detailed behavior of the downstream plasma corresponding to various shock structures must be ascertained.

8.3.6.5 High-Energy Particle Acceleration

The processes governing particle energization by interplanetary shocks remain to be established. It will ultimately be important to determine what properties of the shock studied with satellite instrumentation are transferable to inferred shock phenomena elsewhere in the galaxy.

Progress in further shock investigations will depend heavily on new multipoint, simultaneous spacecraft observations with comprehensive, high-resolution instrumentation and coordinated data analysis. Substantial advances in the description of the earth's total shock system will also result from detailed analyses of a large amount of accumulated observations that now exist. Indeed, certain questions may only be answerable at present using such data. There is a clear need for updated theoretical modeling, and computer simulations should be modified appropriately to correspond to current shock descriptions. Laboratory collisionless shock work should continue, and interactions among researchers pursuing different approaches should be vigorously encouraged.

8.3.7 Kinetic Processes in the Solar Wind

Because of mechanisms not yet completely understood, a small fraction of the solar atmosphere expands outward to fill all of interplanetary space with a fully ionized, electrically neutral, plasma consisting primarily of electrons, protons, and alpha particles. Close to the sun, the expansion is slow and most of the energy and momentum flux is thought to be carried in the form of heat flux and waves. Interpenetrating proton streams (ion jets) may also be present close to the sun and also carry away both energy and momentum. Somewhere between the sun and the orbit of the earth (1 A.U.), this atmospheric expansion picks up speed and simultaneously loses internal energy. Specifically, the energy transported initially in the forms of waves, heat flux, and ion jets is converted, primarily by kinetic mechanisms, into a supersonic bulk convection, or solar wind. This situation is illustrated schematically in Figure 8.7.

Studies of the internal physical state of the solar wind are of scientific interest in their own right as well as for their relevance to several related physical and astrophysical disciplines. For example, such studies provide diagnostic information useful for placing constraints on theories of the solar coronal expansion. They are also of interest toward understanding the development and nature of plasma turbulence in an astrophysical setting. In addition, the solar wind near 1 A.U. provides a laboratory in which several (in general nonlinear) collisionless plasma processes occur. It is therefore possible to use solar-wind observations to quantitatively develop new physical

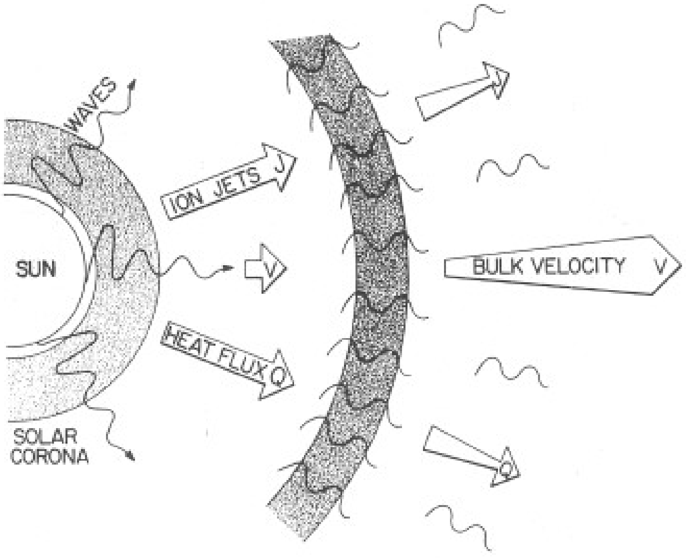

FIGURE 8.7 Schematic illustration of the solar coronal expansion close to the sun. The details of the expansion, including the distance scales, remain to be experimentally verified. The coronal gas, heated by wave damping, is believed to drive an outward heat flux (Q), a bulk convection (V), and, possibly, transient ion jets (J).

concepts as well as to test theories that hope to describe (and eventually allow a control over) the behavior of laboratory fusion plasmas.

A prime example of the applicability to laboratory plasmas is the understanding of heat-flux regulation in the solar wind. A thorough knowledge of all possible heat-flux regulating mechanisms is important since electron heat conduction provides a major means of energy transport in collisionless plasmas. Although the concept of heat flux regulation was first developed for the solar wind, where the flux appears to be under regulation at least some of the time near 1 A.U., it has application for controlling end losses in magnetic confinement devices and for producing spherically symmetric pellet coronas in inertially confined fusion devices.

Another example of the overlap between solar-wind and laboratory-plasma research concerns that of limiting the speeds of ion jets or beams interpenetrating collisionless plasmas. Such jets occur naturally in the solar wind and are at present under investigation for heating laboratory tokamak devices. Recent experimental evidence indicates that the relative speeds of interpenetrating ion beams in the solar wind are being limited by the local Alfvén speed near 1 A.U. The net effect of kinetic processes activated by the relative streaming of ion beams seems to be the formation of nonlinear stationary states. These consist of two interpenetrating, relatively convecting, ion components together with their self-consistent wave fields.

Progress in understanding the physics of at least two other collective kinetic processes that occur naturally in the solar wind near 1 A.U. has also been made recently. These processes are the generation of radio emissions by solar-flare-accelerated electron beams and the *in situ* acceleration of energetic particles. This progress can be briefly summarized as follows: Interplanetary radio emissions have been definitely associated with solar electron beams with energies between ~5 and ~100 keV and are excited at twice the local plasma frequency. Also, the *in situ* acceleration by the solar wind of interstellar neutral particles has been suggested theoretically to explain some observations, although details of the process are not known.

Many topics of intense interest to solar-wind studies such as viscosity, angular momentum transport, collisionless shock structures, and magnetic reconnection have been omitted from this summary because it would be premature to mention them in their present stage of development. Because many of these subjects have important astrophysical applications, considerable effort should be devoted to them in future solar-wind research.

Present and future directions in solar-wind plasma research on the four summarized topics should include the following specific objectives: (1) Measurements in three dimensions of the solar-wind electron velocity distributions should be made on a fine velocity grid for all radial distances inside of 1 A.U. In particular, measurements at radial distances as close to the sun as possible as well as over the solar polar regions will be important for understanding the dynamics of the coronal expansion. (2) Possible heat-flux-driven instabilities should be computer simulated in order to understand their saturation mechanisms as well as their final nonlinear stationary states. An analysis should be made of existing solar-wind data to search for the signatures of all kinetic processes capable of regulating the flow of heat in interplanetary space. (3) High time-resolution measurements of the amplitude and k-vector orientation of plasma waves and electron distributions should be made in interplanetary space (preferably at two radial distances) to understand the mechanism of radio emissions at twice the local plasma frequency by transient electron beams in interplanetary space. (4) High-spectral-resolution measurements of solar-wind ion-velocity distributions in conjunction with ion gyroradius-scale wave fields should be extended throughout the inner regions of interplanetary space in order to determine the original and radial evolution of ion jets. The importance of ions in the transfer of energy from the sun to interplanetary space should also be assessed. (5) Theoretical work is needed in order to understand wave–wave coupling mechanisms and their resulting coupling rates for the general case of obliquely propagating electromagnetic waves. It would then be possible to understand the development of, and assess the importance of, this type of turbulence in the solar wind. (6) Theoretical effort is needed to extend present work on nonlinear plasma equilibrium configurations to include the general case of obliquely propagating electromagnetic and electrostatic waves. (7) Measurements of ion velocity distributions that are capable of a unique identification of singly ionized suprathermal heavy-ion species are needed in order to investigate and understand the processes that result in the acceleration of initially neutral atoms that might be injected into the solar wind from the local interstellar medium.

The above discussion indicates that an integrated program of theoretical and experimental research in solar-wind plasma physics is required. Continued analysis of existing space data promises substantial progress toward identifying and characterizing kinetic processes activated in interplanetary space. Close theoretical support of this analysis is desirable in order to optimize the rate of progress and to achieve a full understanding of the basic physics. Missions consisting of multiple spacecraft are needed to explore and determine plasma conditions throughout the solar system but especially in previously unexplored regions as close to the sun as possible. Many of these missions will require continued monitoring of solar-wind physical conditions near the earth.

8.4 IMPACTS OF IONOSPHERIC–MAGNETOSPHERIC PROCESSES ON TERRESTRIAL SCIENCE AND TECHNOLOGY

Marconi's finding that radiowaves could be transmitted large distances over the surface of the earth probably marks the most significant initial milestone in the utilization of the earth's plasma environment for technological purposes. The discovery of the ionosphere in 1925 as the "reflecting layer" that made possible the radio transmissions led to extensive studies of this region of the upper atmosphere with a view toward both basic understanding as well as better technical use of the medium. Much ionospheric and solar research has been motivated by the disturbances of high-frequency radio propagation at high latitudes during auroral events and solar flares when the reflecting layer is disrupted.

As the technical needs of society have begun to require the utilization of larger portions of the space around the planet, including the placing of sophisticated systems into this space, the impacts of the environment on the systems have created evermore pressing considerations. For example, although modern electronic components and systems are capable of spectacularly efficient performance, their sensitivity to particle radiation means that considerably more accurate models of the space environment than are available at present are necessary, including the understanding of particle flux time dependencies.

In addition to a better characterization of the space environment, the failures and malfunctions of the electronic components and systems that are already well documented to be correlated with changes in charged-particle fluxes require that *in situ* studies of such components and systems be carried out. Field-effect transistors used in low-voltage-level logic switching circuitry are particularly subject to transient effects, such as radiation from localized electrical discharges induced by charged-particle fluxes differentially charging spacecraft materials above their breakdown strengths. The resultant effects include spurious switching of logic circuits into unwanted modes. Inflight studies of surface materials and of deliberately designed mechanisms for compensation of differential charging are required.

As another example, we can cite the necessity for some sophisticated ionosphere research in connection with the contemplated space-based solar power system. Large synchronous-orbiting spacecraft, collecting solar energy on solar cells and beaming it to earth by microwaves, have been proposed by a number of individuals. Although only a small fraction (about a thousandth of a percent) of the beam energy will be absorbed by the ionosphere, this fraction of the power from a 100 W/m^2 microwave beam is comparable with the solar power in the frequency range that represents the major source of heat and ionization in the atmosphere–ionosphere above about 100 km.

As long as technology requires the use of long conductors, near-earth plasma-physics processes will continue to affect such contemporary engineering activities as the interconnection of electrical power grids, the land and sea telecommunications cables, and the electronic monitoring systems on the Alaskan pipeline. Magnetic storms produce disruptions in the electric power grids and outages in long-distance communications. Magnetic fluctuations and disturbances affect pipeline monitoring systems, and the induced currents provide unwanted backgrounds for corrosion engineering studies.

Changes in the regions of occurrence and in the intensities of ionosphere current systems and of magnetospheric waves provide unwanted background effects for petroleum and mineral prospecting, particularly at higher latitudes. Geophysical prospecting must be conducted during geomagnetic quiet conditions. Since such conditions are difficult to predict at present, the dispatching of survey parties during nonoptimum conditions is an accepted fact of life for prospecting companies.

It is not unreasonable to expect from past experiences that as technologies change, subtle and not so subtle physical processes in the near-earth environment will become of importance in determining how some of these technologies will be adapted for use. For example, a long-range impact that solar–terrestrial activity may have on societies is the problem of weather and climate. Evidence exists for possible relationships, on a time scale of decades, between solar activity and climate. Suggestions have been made that on the time scale of days or weeks there is a connection between solar activity, the interplanetary conditions, magnetic disturbances, and hemisphere weather patterns. Specific mechanisms for these processes need to be searched for and found.

In addition, mankind is making impacts on the space environment. For example, in the last couple of years it has been learned that high harmonics from the power grids of industrial North American and European nations are radiated into the magnetosphere and, by some unknown physical process, appear to be greatly amplified. This discovery raises such issues as (a) how increasing industrialization around the world will eventually affect the magnetosphere and ionosphere; (b) whether such changes will be detrimental directly or indirectly to society and/or technology; and (c) whether there is any cause for concern at all.

In summary, it is clear that in addition to the basic scientific importance of space-plasma-physics research, the research has had, and will continue to have important impacts on many aspects of contemporary society and technology.

8.5 DISCUSSION

The preceding two sections summarized the present scientific status of several specific space-plasma-physics topics and the importance of near-earth plasma research for contemporary technological concerns. The recommendations concluding the individual sections discuss the desirability and necessity in the future for appropriate levels of data analysis and theory and of new missions to attack specific scientific questions. In this section we expand on the rationale for these topics. We also comment on the need for popularization of the research results in space plasma physics and of their applicability to societal concerns.

8.5.1 Missions

We recognize that the nation's space program has been, and will continue to be, built on specific spaceflight missions. The great forward advances in future missions devoted to space-plasma-physics topics will result from long-range scientific planning that is specifically problem oriented. This planning will include attention to existing data, to theory (computational and analytical), and to appropriate laboratory experiments.

We note with approval that NASA planning for new near-earth plasma-physics missions has been increasingly problem oriented. We urge NASA to continue the development of new problem-oriented space-plasma-physics missions.

8.5.2 Data Utilization

The recognition of the needs for data analysis and theoretical work, as stressed in the preceding science summaries, is consistent with the 1975 Space Science Board Report, where it was stated that "The level of support for nonmission activities . . . generally falls short, sometimes far short, of the level that would provide an optimum return for the total expenditure on Space Science." The report recognized the need for support in the areas of ground-based observations, theoretical modeling, instrument development, and data analysis. Finally, the report added that it " . . . believes it to be a matter of urgency for the NASA to reexamine its policies in this area, with a view to improving the balance between support for mission and for nonmission activities." It is the consensus of the Panel on Solar System Plasma Processes that the above generalities made by the Space Science Board with regard to space science as a whole apply with full force to our area of specialization.

We acknowledge that the questions of data analysis, theory, and mission support often involve questions of priority in the allocation of nearly fixed resources. We urge continued assessment of the balance between starting new programs and continuing old ones, between hardware development and software support, and between accumulating new data and exploiting data already accumulated. The mechanisms of data handling and dissemination should be reexamined.

As space-plasma-physics missions become more complex and the data more detailed and interrelated among the many mission instruments, sufficient time is required to interpret and understand the data and to place them in proper theoretical context. This cannot necessarily be achieved within an arbitrarily fixed time period, such as one or two years after launch (as is customary at present).

Finally, we note that the data acquired from a successful mission, if properly documented, stored, and made accessible to the present and future scientific community, become an important part of the total value of the project. Many data sets will be repeatedly used by different investigators with fresh perspectives and varying objectives.

Research in space plasma physics requires archived, readily accessible data. The present arrangements for acquiring space-plasma-physics data from mission investigators, as well as the storage and dissemination of these data, are inadequate for their full scientific usage. We recommend that the entire process of mission data acquisition, storage, and dissemination be thoroughly studied in the context of the needs of space-plasma-physics research.

Even technological advances in new satellite instrumentation will not destroy the value of many past data. These data can be reexamined just as eighteenth and nineteenth century sunspot numbers, biblical geographical references, bristlecone pine tree rings, and astronomical plates have been re-evaluated to yield new scientific insights and results.

8.6 CONCLUSION

We believe that during the last two decades the nation has witnessed a revolution in our concepts of the space environment around the earth. We now realize, more than ever, that physical processes operative in the earth's environment and in the solar system are, more frequently than usually credited, used as models for understanding distant objects in the universe. At the same time, these processes can have impacts on technology and society. We conclude that, in the future, a research program in space plasma physics that is problem oriented will lead to continued significant advances in our knowledge and understanding of the natural environment in which the earth exists.

9

Plasma Physics of the Sun

The sun is a ball of gas pouring out of a steady flood of heat. We would expect such a stable, hot, self-gravitating object to be placid and steady throughout its expected life of 10^{10} years, and yet the sun now appears to be anything but steady. The outer layers form a convective heat engine, producing both large- and small-scale circulation. The convection and circulation act as a dynamo to produce magnetic fields, and the behavior of both the circulation and the fields is dramatic and puzzling. The generation of fields by fluid motion is itself remarkable and for a long time was baffling.

It is now known that essentially all astrophysical bodies generate magnetic fields, from the planets and the M-dwarf stars to the galaxy as a whole. The sun is the only star in which the detailed variation of the field can be observed as it progresses through the cycle of generation. The complex field configurations generated on the sun produce continual eruptions of superheated gas and fast particles. It is a general rule that the magnetic fields in the astrophysical universe are active, continually sputtering and exploding with outbursts of energy. The sun is the one place where the activity can be observed at close hand. The observations show that the field behaves in ways that are utterly unfamiliar to our preconceived notions. Fortunately, the sun provides a whole range of new and puzzling effects to guide our thinking. For instance, the magnetic fields of the sun do not spread themselves uniformly over the space available but instead concentrate themselves into intense (1×10^3 to 4×10^3 G) isolated flux tubes, in opposition to the enormous pressure of the field itself. As for the continual activity of these fields, there is now a formal theorem that a magnetic field is subject to neutral point annihilation and rapid reconnection if the topology of the lines of force is not suitably invariant along the field. Thus, even if we do not yet comprehend the detailed structure of the individual outbursts, we may

understand the general basis for continual activity. Sometimes the outburst is of such gigantic proportions that it dominates interplanetary space for a time with superheated gases and relativistic particles. But it is not yet clear how the dissipation of a magnetic field can be so efficient in the acceleration of a few selected particles to such extraordinary energies. The recent observational discovery that some flares spit out more ^{3}He than ^{4}He, while producing essentially none of the accompanying spallation product ^{2}H, suggests either some special resonance effects or that the flare is the result of intense, isolated current filaments in a force-free magnetic field.

These effects are probably common to all stars, some of which are more active than the sun. But, again, the sun is the only star close enough to observe in detail what is happening. We are reminded of how detailed studies of the solar chromosphere and corona led to the development of the complex theory of the stellar atmosphere that is not in local thermodynamic equilibrium. The theory is now applied successfully to the atmospheres of the other, more distant stars, yielding reliable abundances of the elements and meaningful structures for those stars. The sun is again serving as a prototype, showing that many explanations for magnetic activity, now applied so readily to the unresolved activity of more distant stars, are naive in light of recent, detailed observations of solar magnetic fields. The theory of fluid electrodynamics does not, so far, supply an explanation for the concentration of broad fields into isolated, intense flux tubes, nor does it account for the details of the activity of those fields. The development of the theoretical concepts, however, is progressing at a rapid pace, aided by the recent improvements in observational resolution, by the extension of observations into the ultraviolet and x-ray regions, and by information on the isotopic abundances of fast particles. The new observations raise new questions, of course, while delimiting the answers to old questions, so that the active development of understanding is currently entirely open ended.

The convection and circulation in the sun are responsible for both the production of magnetic field and for the delivery of heat to the surface of the sun. There is, at present, a determined theoretical effort to understand the hydrodynamic circulation in a convecting, rotating, stratified gaseous sphere such as the sun. It is a problem in classical physics that challenges the best analytical and computational methods available. Efforts are also being made to refine the observational techniques so that the large-scale circulation and convection can be observed and mapped to check on the theoretical results.

It has also come to light, largely through the historical research of Eddy (and the earlier work of Maunder), that the magnetic activity in the sun is sometimes completely absent for a period of 50–100 years. The most recent occurrence was in the seventeenth century, at a time when sunspots were carefully observed and recorded with telescopes. The attendant increase in the cosmic-ray intensity shows clearly in the production of ^{14}C at earth. The ^{14}C record shows that the activity switched off again in the fifteenth century, and in the fourth, seventh, and fourteenth centuries B.C. The only interpretation of the absence of activity is that the production of magnetic field was greatly reduced from the present levels, indicating that in some way the circulation and convection changed so as to be less effective in the generation of field. The effect may not be unlike the abrupt changes in the global circulation pattern of the atmosphere of earth, sometimes persisting for years. Eddy, Gilman, and Trotter have shown from the old observational records of sunspots that the nonuniform rotation of the sun (as determined from the motion of the sunspots across the solar disk) was strikingly different as the sunspots were disappearing in 1640–1645, with the region of high angular velocity concentrated much more closely to the equator than at present. But the most outstanding aspect of the change in circulation is the implication that the change cannot fail to alter the delivery of heat to the surface of the sun, producing some small temporary change in the total luminosity of the sun or slightly redistributing the brightness between the pole and the equator. Either change by as little as one part in 10^2 would have profound effects on the temperature of earth, amounting to a change in the mean annual temperature of a degree or more. The historical and geological records show that the centuries of solar inactivity coincided in every case with the centuries of cold weather in the northern temperate zone of earth. The problem is clearly more than just an intellectual challenge when we realize the consequences of the temperature changes on our food supply. The social and political problems associated with the cold weather of the fifteenth and seventeenth centuries are a matter of historical record, both in China and in Europe.

The sun is not a laboratory permitting the introduction of instruments into the active plasma, as in the magnetosphere of earth and the solar wind. It is instead a *demonstration* laboratory, where the effects are displayed and can be observed and diagnosed from a distance. The variety of the unknown effects is established by present observations. It is interesting to reflect on how much is known and understood now that was not known, or at least not understood, 10 and 20 years ago. But the problems still unsolved are fundamental in both the scientific and practical senses of the word. Their study is basic to the rest of astrophysics and to understanding important aspects of both the past and future of the human race.

APPENDIX 9.A: PROGRAM OF SOLAR RESEARCH

Table 9.A.1 is an outline of a comprehensive program of solar research that summarizes the major problems and the tools needed for their solutions.

This was published as Table 6 in the 1975 SSB Study on Solar Physics that was published in *Report on Space Science, 1975.* It is republished here to remind the reader of the scientific objectives of solar research that served as an important contribution to the identification of the future objectives of research in space plasma physics. The table is an outline *only*—the reader is urged to read the earlier report, in conjunction with this one, in order to understand fully the details of the research program.

TABLE 9.A.1 Program of Solar Research

Area	Problem	Tools for Its Solution
I. Flares	(a) Buildup and dissipation of magnetic fields	(a) Temporal and spatial magnetograph data, with concurrent soft x-ray and radio imagery, theoretical dynamical studies
	(b) Location of the energy release and particle acceleration	(b) Hard x-ray imaging and spectroscopy; gamma-ray and energetic beam impact-point observations; high-resolution microwave mappings; fast meter–decameter radioheliograph
	(c) Thermal history of the flare plasma	(c) High-resolution visible, uv, xuv, x-ray, and centimeter-wave imaging, and spectrophotometry
II. Active regions	(a) The nature of sunspots; why are sunspots and flare knots stable?	(a) Theoretical studies of basic dynamical effects in sunspot structure; observational studies of wave fluxes from sunspots; very highly resolved magnetograms and optical data; theory
	(b) Structure and dynamics of coronal condensations	(b) High-resolution visible, uv, xuv, x-ray, and radio imaging, and spectrophotometry
	(c) Evolution of active regions	(c) Synoptic studies at visible, radio, uv, and soft x-ray ranges
	(d) The properties of prominences	(d) Highest resolution euv, visible, and radio observations; theoretical studies
III. Magnetic cycle	(a) Dynamics of sunspots, energy balance of spots	(a) Highly resolved magnetograms and euv and optical data; theory plus time-resolved magnetograms, optical data (including velocities)
	(b) How rapidly and in what way do coronal fields evolve (dissipate)?	(b) ATM data analysis; coordinated synoptic x-ray/xuv and magnetograph data with adequate time resolution (minutes to hours?)
IV. Solar interior	(a) Hydrodynamics of convection and circulation	(a) Theory, computer modeling
	(b) Large-scale circulation	(b) Extremely high sensitivity measures of velocity and rotation
	(c) Origin of the solar magnetic fields	(c) Synoptic observations of solar magnetic field with modest resolution, velocity, and magnetic-field observations of polar regions of sun
V. Quiet sun	(a) What is the velocity field in the transition zone and corona?	(a) Xuv spectroscopy with high spatial and spectral resolution, moderate time resolution; x-ray, xuv, radio imagery
	(b) What is the role of magnetic fields in heating?	(b) High-resolution magnetograph, visual, xuv, x-ray data; ATM data analysis
	(c) Are time-dependent ionization effects important in the dynamically varying quiet sun?	(c) Xuv line radio observations, velocity observations, theory
VI. Coronal structure	(a) The distinctive structure of the quiet corona and coronal holes; coronal transients	(a) Imaging and spectroscopy in visible uv, xuv, x rays; high-resolution magnetic fields; fast meter–decameter radio heliography
	(b) Coronal magnetic fields	(b) Radio polarization observations, white-light coronagraph polarization studies
	(c) Heating mechanisms	(c) Development and coordination of theoretical modeling with empirical models; observation of coronal temperature and density structure with white-light and Lyman-α coronagraphs; xuv and soft x-ray line profiles

TABLE 9.A.1 Program of Solar Research (*continued*)

Area	Problem	Tools for Its Solution
VII. Solar wind	(a) Relation of solar wind to coronal holes, active regions	(a) Complete coordinated data on corona and solar-wind parameters; theory and computer modeling; extend interplanetary data closer to sun and out of the ecliptic
	(b) Angular momentum of solar wind and loss of angular momentum from sun over its evolution	(b) Well-calibrated observations of angular momentum of solar wind, ultimately out of the ecliptic
	(c) Solar wind and cosmic-ray conditions at middle heliocentric latitudes and over the polar coronal holes	(c) Out-of-the-ecliptic missions
VIII. Composition	(a) Chemical composition of solar wind and relation to corona	(a/b) Better composition measurements of solar wind; theory of ionic diffusion in transition zone and separation in solar wind
	(b) Chemical and isotopic composition in solar flares	
	(c) Fractionation in the solar corona	(c/d) Solar cosmic-ray observations with good elemental and isotopic resolution; gamma-ray data with high sensitivity; xuv and soft x-ray abundance studies
	(d) Fractionation in solar flares	
IX. Solar–terrestrial relations	(a) Ozone variations with uv, cosmic-ray variations, geomagnetic activity	(a) Synoptic observations of solar ultraviolet emission; upper atmosphere, magnetospheric studies
	(b) Effect of ozone concentration on global circulation pattern	(b) Improved atmospheric modeling
	(c) Possible relationship between weather, climatic, and solar activity	(c) Continue the coordination and statistical study of solar, interplanetary, and terrestrial conditions
	(d) Long-term climatic changes due to changes in solar constant	(d) Precision synoptic observations of total solar luminosity