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Solar-Terrestrial Research for the 1980's

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Abstract: Solar-terrestrial physics is the study of the complex physical system but which the energy and matter emitted by the sun at variable rates are transmitted through the interplanetary medium to the terrestrial

magnetosphere-ionosphere-atmosphere subsystem. This report describes the solar-terrestrial system and emphasizes that it should be treated as a unitary entity of interlocking chains of phenomena which should be studied together rather than separately. It directs attention to those domains and interconnections that are not adequately understood. It proposes promising techniques for bridging these gaps by observations involving all relevant platforms -- spacecraft, the earth's surface, aircraft, balloons, and rockets. It contains a set of eight recommendations for scientific study, which if taken as a package, should lead to a balanced program in solar-terrestrial research for the 1980's. It also emphasizes the need for interagency coordination of programs, efficient data management, theoretical studies and modelling, the continuity of long time-series observations, and innovative instrument design. A final chapter gives examples of the practical impact of interactions between solar-terrestrial phenomena and the environment, including technological systems.

Descriptors: *Magnetosphere, *Ionosphere, *Interplanetary medium, Thermosphere, Solar magnetic fields, Solar wind, Research, Reviews

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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Geophysics Research Board
2101 Constitution Avenue
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Solar-Terrestrial Research for the 1980's

STUDY PARTICIPANTS

HERBERT FRIEDMAN, *Co-chairman*

Naval Research Laboratory

DEVRIE S. INTRILIGATOR, *Co-chairman*

University of Southern California and Carmel Research Center

MURRAY DRYER

National Oceanic and Atmospheric Administration

JOHN A. EDDY

National Center for Atmospheric Research

JOHN V. EVANS

Massachusetts Institute of Technology

PETER FOUKAL

Atmospheric and Environmental Research, Inc.

J. R. JOKIPII

University of Arizona

FRANCIS S. JOHNSON (through July 1979)

University of Texas at Dallas

LOUIS J. LANZEROTTI

Bell Laboratories

GEORGE A. PAULIKAS

The Aerospace Corporation

GEORGE C. REID

National Oceanic and Atmospheric Administration

RAYMOND G. ROBLE

National Center for Atmospheric Research

JUAN G. ROEDERER

University of Alaska

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University of Maryland

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NASA Goddard Space Flight Center
MARTIN A. POMERANTZ
University of Delaware
EDWARD J. SMITH
Jet Propulsion Laboratory

Magnetosphere/Ionosphere System

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National Meteorological Center

P. A. GILMAN
National Center for Atmospheric Research

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Bell Laboratories

R. J. McNEAL
National Aeronautics and Space Administration

J. MURRAY MITCHELL, JR.
National Oceanic and Atmospheric Administration

GEORGE C. REID
National Oceanic and Atmospheric Administration

Foreword

In this study of solar-terrestrial research, emphasis has been placed on achieving unifying concepts through which the science of the whole sun-earth system becomes greater than the sum of its component parts. To attain this goal, the scientific focus is placed on the interactive processes among the various physical regimes.

Also considered are various general issues of coordination and organizational aspects of a national program in solar-terrestrial research now distributed among various supporting agencies, such as the National Science Foundation, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the Department of Defense. The report includes discussion of some well-established and some not so well-established impacts of solar-terrestrial research in order to bring out the importance of the application of scientific knowledge, public policy issues, and the connections with the missions of the various agencies.

The members of the study group and its more specialized disciplinary working groups were chosen to provide broad competence in the various aspects of solar-terrestrial research (STR). In addition, reviewers who were not associated with any disciplinary group of the study were selected to help develop a balanced view of the entire field out of the more-specialized interests of the discipline-oriented groups.

The study took over 18 months to complete and involved the participation of more than 50 scientists. This report was reviewed and endorsed by the full Committee on Solar-Terrestrial Research in December 1980 before its submission to the National Research Council for review and publication.

The Committee on Solar-Terrestrial Research wishes to take this opportunity to thank the participants of this study for their efforts. Special thanks are due to the Co-chairmen, Drs. Friedman and Intriligator, whose patience, perseverance, and hard work made this report possible. The contributions to the preparation of this report by Edward R. Dyer, Jr., Secretary of the Committee on Solar-Terrestrial Research, who served as study director, and by Helene E. Patterson, his secretary and assistant, are also gratefully acknowledged. The cooperation and support of the various agency officials, especially E. W. Bierly, H. C. Carlson, A. J. Grobecker, and D. S. Peacock of the National Science Foundation, H. Glaser, E. R. Schmerling, S. G. Tilford, and A. Timothy of the National Aeronautics and Space Administration, and R. H. Manka, A. H. Shapley, and D. J. Williams of the National Oceanic and Atmospheric Administration were invaluable.

John V. Evans, *Chairman*
Committee on Solar-Terrestrial
Research
July 1980-

Andrew F. Nagy, *Chairman*
Committee on Solar-Terrestrial
Research
July 1977-June 1980

Preface

The decade of the 1980's holds great promise for exciting research opportunities as well as a variety of challenges for the field of solar-terrestrial research. The past two decades constituted the "age of discovery": Van Allen radiation belts, coronal holes, and the fragile nature of the ozone layer are just a few examples of the many new phenomena discovered during that period. The next step toward a thorough understanding of our solar-terrestrial environment requires a well-planned and organized effort to elucidate the physical and chemical processes controlling its complex interactive behavior.

Since its formation in 1965, the Committee on Solar-Terrestrial Research (CSTR) of the National Research Council's Geophysics Research Board has been charged to "look after the health of this field." The last studies conducted under the auspices of the National Academy of Sciences to consider a comprehensive national policy toward spaceborne and ground-based research in this area were carried out in the late 1960's. Several excellent studies have been done more recently; however, these dealt only with certain subdisciplines of solar-terrestrial research (STR) or were addressed to the needs and interests of only a single federal agency. The CSTR, after careful deliberation and extensive discussions with chairmen of other appropriate committees as well as with officials of the federal scientific agencies concerned, decided to commission a study to recommend an optimal, coordinated national program for solar-terrestrial research in the 1980's. The objectives were as follows:

1. Identify the contributions to the key scientific challenges of solar-terrestrial research that can be made by various government agency ground-based and space-based programs as well as information gleaned from NASA

applications missions and other projects not intensively examined by previous Space Science Board studies.

2. Develop a rationale for unifying the study of the entire solar-terrestrial system.

3. Recommend a balanced national program for the 1980's to supplement the recommendations of the Space Science Board.

The response to these goals was to be supplemented by a concise but comprehensive scientific treatise on STR addressed to the scientific community at large and to the government agencies committed to the support of STR.

Desirable programs and new facilities together with suggested means of coordinating them with each other and with NASA programs (in solar-terrestrial research) were to be identified. The formulation of programmatic details and mission plans remains the responsibility of the funding agencies.

The report has two parts. Part I contains Chapters 1-4 and is concerned with programmatic decision processes in federal agencies, research institutions, and the community of workers in the field. Part II, containing Chapters 5 and 6, provides a scientific description of the solar-terrestrial system for general background information and discusses some related societal impacts.

It should be emphasized at the outset that we have deliberately not assigned priorities to the eight scientific recommendations or the five general recommendations given in Chapter 2, for different reasons in each instance. The eight scientific recommendations constitute *an integrated set* dealing with the regimes in question, but more particularly with their interconnections, such that the chain would be severely weakened by the omission of any one recommendation. The general recommendations on management policies that complete Chapter 2 are concerned with different activities and complement each other.

Chapter 1 is a brief overview of STR and includes some historical perspective to suggest guidelines for future cooperative arrangements. Certain elements of commonality between solar-terrestrial research and contemporary studies in astrophysics, planetary physics, and laboratory plasma physics are pointed out. Some societal impacts of solar-terrestrial research are also noted.

The set of major scientific recommendations in Chapter 2, as already mentioned, emphasizes the interaction of the various elements of the solar-terrestrial system. The outstanding scientific problems that the carrying out of these recommendations is intended to solve are discussed in Part II, Chapter 5. These recommendations are also to be understood in the context of the previous recent Academy studies that are described in the Appendix. In the last half of Chapter 2, a set of management recommendations addresses some general questions, such as interagency coordination of the broader national

effort, data management, support of theory and the modeling of observations, and commitment to continue long-time series of certain types of observations. Additional background for these general management recommendations may be found in Chapter 3, which also looks at the changing sociology of the community of scientists who are being drawn to the field.

Chapter 4 describes implementation plans by which a program to achieve the scientific goals of solar-terrestrial research in the 1980's can be carried out. It deals with both observations and theory. On the observational side, previous studies have already dealt so thoroughly with space-based techniques that it is appropriate to reaffirm our support for them without rediscussing them in detail. The emphasis is therefore on ground-based and suborbital methods of observation, and ways to achieve an optimum synergism between these methods and space missions. Theoretical studies and computer modeling are such an intrinsic component of each of the individual STR disciplines identified in Chapter 1 that a single section has been devoted to the general need for such studies across all of STR. An observational program designed to implement the scientific goals is outlined, section by section, according to these same disciplines. It contains recommendations for specific kinds of observations that are keyed to the recommendations in Chapter 2. They are thus fairly selective and do not attempt to include all conceivable techniques. Some additional theoretical problems specific to each discipline are also noted.

Part II, Chapter 5, gives the scientific background needed to provide the rationale for the scientific recommendations, with emphasis on those unsolved problems that challenge the scientific community. This chapter concludes with a summary of the relationship between comparative planetary studies and solar-terrestrial research. Chapter 6 describes applications of STR to various environmental and technological problems.

This study deliberately excludes classical meteorology, a discipline so broad and complex and with such a long historical independent development of its own that it has traditionally been treated separately from solar-terrestrial research. The dividing line between the effects of solar-energy input to the troposphere and the rest of the atmosphere, however, is logically hard to maintain and is in fact becoming blurred. Perhaps some day both fields will be unified as a single discipline.

Herbert Friedman
Devrie S. Intriligator
Co-chairmen of the Study

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Part I

1

Overview of Solar–Terrestrial Research and Its Impacts on Applied Science and Technology

I. INTRODUCTION

Solar–terrestrial research (STR)—often also called solar–terrestrial physics or solar–terrestrial relationships—in its broadest sense, is concerned with the processes by which diverse forms of energy generated by the sun influence the terrestrial environment and with the resulting complex interplay of the physical-chemical processes in every element of the sun–earth system. (See Figure 1.1.) Solar–terrestrial research emphasizes the variable component of solar-energy production and its transport to the earth, but it includes a study of the hypothetical steady state of each of the elements of the sun–earth system insofar as this provides a necessary baseline from which to measure the variations. It deals with the direct irradiation of the upper atmosphere by the full spectrum of electromagnetic radiation and with the transport of particles and fields from the sun, through the interplanetary medium, to and through the magnetic field of the earth and into its atmosphere. Most of the solar energy that is eventually deposited in our atmosphere (at a rate of about a trillion or 10^{12} MW) arrives in the form of visible light. The study of this interaction process is the province of meteorology, a discipline that has enjoyed a long and independent development of its own and has its own complex problems, sufficiently different from solar–terrestrial research in the narrower sense that the two are regarded as separate but neighboring disciplines. In this narrower sense, solar–terrestrial research is concerned with those higher-energy radiations—ultraviolet, x-ray, and gamma—that carry only a tiny fraction of the total power (about 10^6 MW) but that have significant and highly variable effects on the terrestrial environment. The rate of transfer

THE SOLAR-

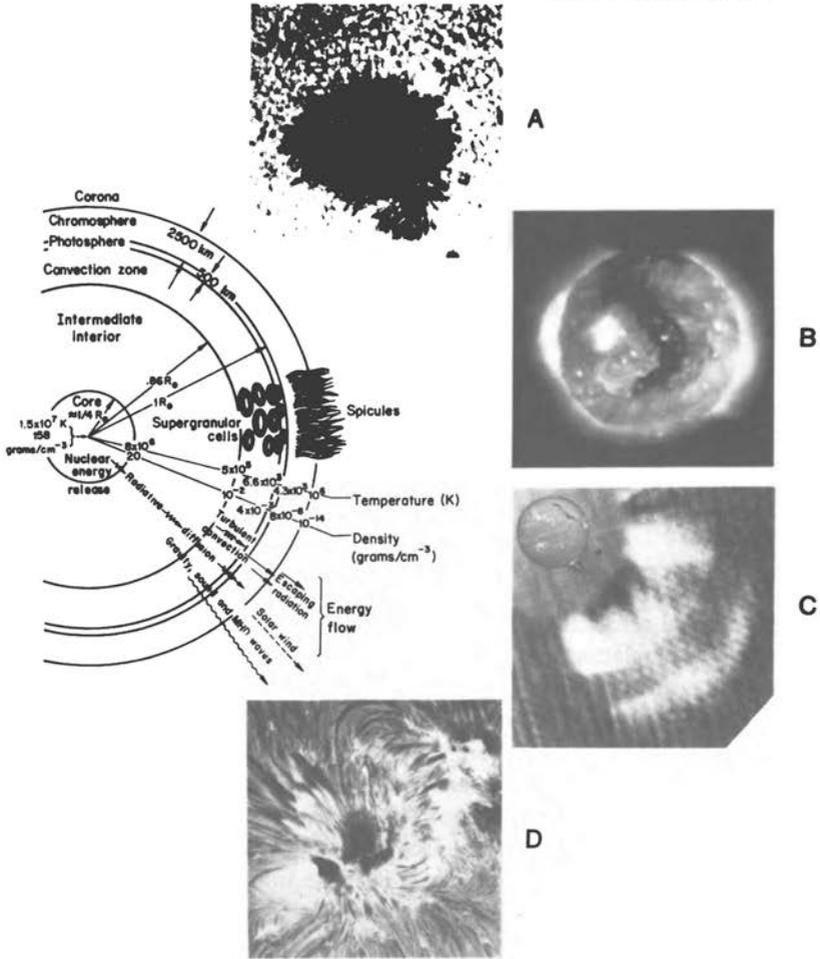
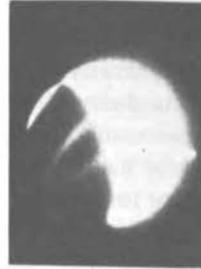
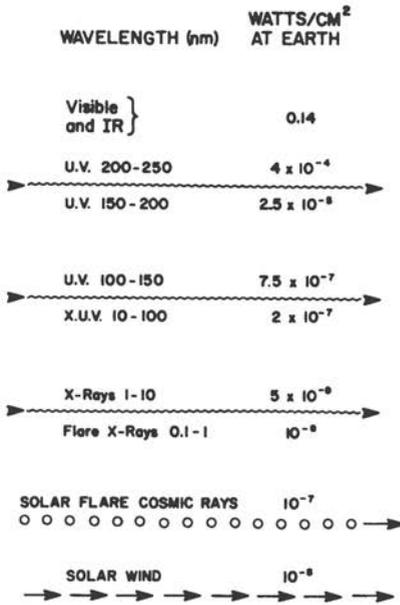
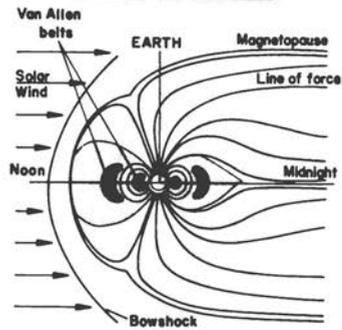


FIGURE 1.1 The solar-terrestrial system. *Schematics*. On the left: Idealized solar properties, structures, and modes of outward energy flow. (After *The Quiet Sun*, E. G. Gibson, NASA Publication SP-303, 1973, Figure 2-3.) The dimensions of the concentric regions and the features are not to scale. Right center: Typical power fluxes of solar electromagnetic and particle radiation and of the solar wind, as measured at the earth's magnetosphere at far right. *Photographic insets*: A, A sunspot surrounded by the quiet photosphere with granulation. The field of view is several times the diameter of the earth. B, X-ray image of the sun showing a relatively cool, hence dark, coronal hole reaching from the north pole and winding across the solar equator toward the

TERRESTRIAL SYSTEM



E



INTERPLANETARY MEDIUM



F

south pole. C, An image of the inner corona taken with the NRL SOLWIND coronagraph (satellite STP-78-1), on which is inset a monochromatic image of the solar disk (upper left corner). It shows an erupting cloud of plasma that has expanded to 4 million km (about 6 solar radii) in the 3 h following the onset of the flare surge shown in the inset. D, A solar flare photographed in the monochromatic light of the red line of hydrogen, H-alpha. E, Far-ultra-violet airglow emission from atomic oxygen at high altitudes in the earth's atmosphere, photographed from the moon during the Apollo 16 mission. (NASA/NRL photograph.) F, Aurora photographed over College (near Fairbanks), Alaska.

of other kinds of energy from the solar wind to the magnetosphere-ionosphere-atmosphere system is even smaller but is of so highly specialized a nature that its observable effects are far-reaching.

STR is necessarily but only indirectly concerned with the deep interior of the sun, where the thermonuclear energy is generated, and with the transport of that energy to the solar surface, to the extent that variability in these processes influences the solar output. Similarly, at the end of the chain linking sun and earth, STR is again only indirectly concerned with the behavior of the fluid core of the earth where the flow of electric currents generates the powerful terrestrial magnetic field that extends out into space. STR deals with paleomagnetism to the extent that it reveals the historic variability of the earth's magnetic field, which must have had profound implications for past solar-terrestrial interactions, and to the extent that it may help to forecast significant trends for the long-range future. Also, historical records of climatic changes, correlated with tree-ring records and descriptions of the aurora, provide invaluable resources for retrospective research.

The sun drives the circulation of the atmosphere, which in turn produces the weather. It draws water from the oceans into the air to produce clouds, rain, and snow. These phenomena constitute the subject matter of meteorology. The boundary between that much older discipline and its younger sister, solar-terrestrial research, was originally quite distinct but is becoming rather blurred as the two have met in the lower stratosphere. For example, the interface between the troposphere (the lowest 10-15 km-thick layer in which the weather is generated) and the stratosphere and the flow of energy and matter across the interface is of interest to both disciplines. STR is also concerned with the possibility that solar variability directly or indirectly affects the weather and climate, as some believe, but our present understanding does not yet permit an unambiguous answer to this question. It is already well known, however, that solar variability does affect the magnetosphere, ionosphere, and atmosphere above the troposphere. If there eventually proves to be a solar activity-weather connection, its implications for long-range forecasting and climatological predictions may be important.

Finally, only the fullest possible understanding of the physics and chemistry of the solar-terrestrial system will make it possible to estimate the effects of growing human activity on our environment.

II. GLOBAL CHARACTER OF SOLAR-TERRESTRIAL RESEARCH AND INTERNATIONAL PROGRAMS

Because research in STR has an intrinsically global character, cooperative studies on a national and international basis are especially productive. The

beginning of the development of modern STR can be traced to the rather limited goals of the first International Polar Year, almost exactly 100 years ago, when several nations mounted a concerted effort to study arctic weather. That scientific endeavor subsequently spawned a succession of international cooperative programs on a global scale. Fifty years later, in 1932-1933, radio science had revolutionized concepts of the high atmosphere, and the Second International Polar Year was called into action. The end of World War II left a legacy of rocket technology that was readily adaptable to upper-atmosphere research and paved the way to an era of spacecraft exploration with results that revolutionized science of the upper reaches of the terrestrial environment. Until then, progress in direct probing at high altitudes had advanced slowly from the primitive nineteenth-century use of kites for measuring stratospheric temperature to the more advanced techniques made possible by balloons. By the 1950's, ground-based and space research techniques had advanced to the point where dramatic results could be expected; to take advantage of these new capabilities, the International Geophysical Year (IGY) was organized. The planning was on the largest scale ever attempted for a program that depended on international scientific cooperation. In its first year (1957), 116 rockets were launched and thousands of scientists were involved in ground-based efforts. That same year produced Sputnik; the following year the U.S. placed Explorer I in orbit, leading to the discovery of the Van Allen radiation belts.

The IGY demonstrated the power of global cooperative studies of the sun-earth system so convincingly that it became imperative to preserve its organizational style and to sustain the momentum of cooperative research. Thus, it was followed in 1964-1965 by the International Years of the Quiet Sun (IQSY), in 1976-1979 by the International Magnetospheric Study (IMS), currently by the Solar Maximum Year (1979-1981), and soon will be followed by the Middle Atmosphere Program (1982-1985).

Although progress in STR has been spurred by international programs, a sustained national effort is essential to preserve healthy progress and full access to new results by the U.S. scientific community and U.S. industrial and governmental users. The IMS was characterized by a carefully planned and executed coordination of ground-based and space-based observations and is resulting in great advances in scientific knowledge. We expect that the national program for the 1980's will continue to foster such coordination wherever necessary.

Effective data management has become a crucial ingredient of coordination for a long unbroken series of observations of parameters such as the solar constant and atmospheric ozone concentration, which are needed in order to understand the sensitivity of the earth's environment to small changes in energy input.

III. NATURAL AND ARTIFICIALLY INDUCED INTERACTIONS

Current work in solar-terrestrial research truly has its roots on the ground, while its manifold branches reach as far out as instruments can probe the solar system. The special scientific attraction of STR is that with today's space-age technology practically all the components of the sun-earth system are accessible to *in situ* scientific observations, and some controlled experiments are even possible. At the same time, ground-based systems can routinely and easily observe phenomena that are physically linked to remote regions of the earth's environment. In this situation there is a reversal of the usual one where the need is for "ground truth" associated with observing programs from space—the *in situ* space observations provide "space truth" for networks of ground-based observatories.

The past two decades have, in fact, provided samplings of almost every element of the solar-terrestrial system to the extent that local properties of all regimes are substantially well characterized. What is desired from the research of the 1980's is a quantitative appreciation of all the significant couplings, trigger mechanisms, and feedback processes. Of practical concern are chains of processes that have end results important to life processes, effects on communication and technological activities, and impacts on the conduct of scientific observation of natural phenomena. For example, in recent years considerable attention has been devoted to the natural chain of production and to the effects of human activity on stratospheric ozone. Biological organisms are protected from lethal influences of short-wavelength ultraviolet light by ozone in the earth's stratosphere, and thus any major change in stratospheric ozone abundance is of serious concern. In another context, the development of solar power stations in space may require ion engines to transfer such stations from low earth orbit to synchronous orbit. The injection of foreign constituents from the exhausts of these engines into the upper atmosphere/magnetosphere may distort the natural particle environment and substantially affect the stability of the radiation belts. Beaming enormous microwave fluxes from a solar power station through the ionosphere could adversely impact communications.

Mankind must be concerned that natural or man-generated perturbations, themselves intrinsically small or weak, do not trigger cataclysmic changes through nonlinear runaway mechanisms. For this reason, it would be dangerous to downgrade or totally ignore the study of any of the elements that we have not yet specifically identified in the solar-terrestrial system. We have not inhabited the earth long enough to see the system go through more than a tiny fraction of its possible excursions. Industrial and other human activities are tampering with the controls of "Spaceship Earth" even before we know completely how the system works. That is why intensive, basic scientific study

of the whole interactive solar-terrestrial system is so relevant to understanding possible societal impacts and deserves a commensurate priority among those scientific disciplines that offer prospects of practical opportunities.

IV. RELATIONSHIPS TO OTHER SCIENTIFIC FIELDS

The main objective of STR is to understand the two principal energy transport processes connecting the sun with the earth: the direct solar radiation linkage and the particles-and-fields connection. Related processes in planetary science and astrophysics are also important, however, in illuminating processes in the sun-earth system. Unlike laboratory physics, where experiments can be totally controlled, the sun-earth system is largely beyond human control. Small injection experiments in the magnetosphere (e.g., releases of chemicals or directed charged-particle beams) are possible, and large inadvertent experiments (e.g., global chlorine releases from aerosol sprays or high-altitude nuclear-weapons tests) have taken place, but large-scale systematic experiments on the functioning of the solar-terrestrial system itself are not possible or clearly desirable. In these circumstances, the study of partially analogous systems, provided by the other planets, is a useful substitute for experiments. Indeed, studies of the magnetospheres and atmospheres of the other planets, having a wide range of scale sizes and boundary conditions, provide insights into the behavior of the terrestrial system. For example, with Venus we have a planet that lacks a perceptible magnetic field, a condition that conceivably could apply to the earth during magnetic-field reversals. Mercury has a magnetic field but no atmosphere—only a magnetosphere. Mars is different again; each planet illuminates special aspects of the behavior of the terrestrial environment as one parameter or another is maximized or minimized.

In a similar way, while we must attempt to understand the sun as we observe it, studies of other stars can offer useful insights into fundamental stellar processes. For example, the Skylab Mission has demonstrated the enormous complexity of the processes involved in the formation and maintenance of the hot, outer solar atmosphere, the corona. This was accomplished without great difficulty mainly because the sun is sufficiently close that our instruments can resolve many of its features. Our ability to study corresponding features of other stars has been minimal because we cannot observe them other than as point sources. In the last two years, however, breakthroughs have occurred in stellar astronomy that carry potential implications for STR. The launchings of the International Ultraviolet Explorer satellite (IUE) and of High Energy Astronomical Observatories (HEAO) have allowed us to observe for the first time other stars with sufficiently great sensitivity in the high-energy portion of the spectrum that the hot, outer atmospheres of giants and

dwarfs, as well as of solar-type stars, are detectable, and important general properties of stellar atmospheres have been deduced. Observations with the Einstein x-ray telescope have shown that coronal structures are not exclusive to stars like the sun. Coronal x-ray emission may be observed in early- and late-type stars (those hotter and cooler than the sun) as well. These new observations challenge conventional ideas about stellar interiors and the modes of energy transport to and through the stellar surface. The sun has been, and will continue to be, the testing ground of stellar astrophysics. Theoretical modeling of the solar atmosphere should throw light on the earlier and later phases of evolution of hydrogen-burning stars.

The large-scale escape of dilute plasma from the sun, termed the solar wind, also represents a phenomenon that occurs in many galactic and extragalactic objects. The study of processes occurring in the solar wind, for example, the interaction between turbulence, shock waves, and energetic particles, will provide insights to phenomena that occur in many astrophysical contexts.

STR not only benefits from related scientific studies but contributes to them. Space research has already played a pivotal role in fundamental plasma physics. For example, crucial to theories of solar flares and magnetic disturbances (magnetic substorms) in the magnetosphere is the concept of magnetic-field reconnection. This process is undoubtedly equally important for astrophysical plasma processes occurring on cosmic temporal and spatial scales. Only recently has it been possible to observe evidence of reconnection phenomena on the sunward side of the magnetospheric boundary from spacecraft employed in the IMS. The reconnection process is so basic to so many areas of plasma physics that further study, both theoretical and experimental, must be accorded the highest priority.

In many other respects, the scale of solar-system plasmas provides us with a helpful bridge between the spatially restricted studies of laboratory plasmas and the ultimate cosmic plasma generators of incredibly great energies. The only astrophysical system in the universe that will be directly accessible to *in situ* examination for generations to come will be the solar-terrestrial system. An understanding about how it works must, at the very least, provide useful bounds on our interpretation of the nature of other astrophysical objects.

V. COMPONENTS OF THE SOLAR-TERRESTRIAL SYSTEM

The sun, the interplanetary medium, the magnetosphere/ionosphere, and the atmosphere make up the solar-terrestrial system. Each of these components is briefly described here, with emphasis on those features that play a part in the chain of solar-terrestrial phenomena. They are discussed in greater detail in Part II.

1. The Sun

The sun is a star of average mass and luminosity whose remarkably steady output of radiation over several billion years has allowed life to develop on earth. However, the balance in the existing ecosystem is fragile, and the small variations in output of solar radiation and particles that are known to exist have practical and significant impact on man's environment. Variability is most obvious in the magnetic fields observed directly at the visible solar surface—the photosphere. These fields exhibit a quasi-regular cycle, during which the changes in the polarity of the global magnetic structure repeat themselves over a period of close to 22 years. The 11-year variation in number and latitude distribution of magnetic sunspots is the most easily observed aspect of this 22-year magnetic reversal.

The amplitude of the oscillation of solar magnetic fields, as evidenced by sunspot numbers, is known to have varied greatly in historical times (Figure 1.2). For example, there was an extended interval from 1645 to 1715 when sunspots were rare, known as the "Maunder Minimum." It coincided with the most significant drop in temperature over the region for which there is reliable information, within a longer interval known as "the little ice age." This and other less well-established coincidences have led to speculation that there is a connection. Similarly, the history of droughts in the southwestern high plains of the United States, which exhibits a cycle of about 22 years, appears to be roughly synchronized with the 22-year solar magnetic cycle.

Potential correlations between the prehistoric sunspot cycle and the paleoclimatic record can be investigated in the following way. It is known that the flux of cosmic rays at the earth is modulated by the extension of the solar magnetic field into the interplanetary medium, the strength of which, as we have seen, is greatest during the maximum phase of the cycle of solar activity. The cosmic-ray flux at the earth is thus smallest during the maximum phase. The cosmic-ray bombardment of the terrestrial atmosphere produces radioactive carbon that enters the life cycle of plants, more copiously at solar minimum than at solar maximum. Thus radiocarbon leaves a cyclical imprint on the tree rings in the oldest living things, the 4500-year-old bristlecone pines of eastern California, and in still older archeological remains and serves as a proxy indicator of sunspot numbers for the past few thousand years, permitting comparisons with the paleoclimatic record.

Prompt manifestations of changes correlated with solar magnetism lie in the relatively large variations in x-ray, ultraviolet, radio, and particle emissions that accompany the magnetic changes. For instance, the hard x-ray emission at times of peak sunspot number is typically 100 times the flux measured at times of sunspot minimum. The most explosive eruptions that occur in the solar atmosphere are the spectacular solar flares. In a matter of minutes

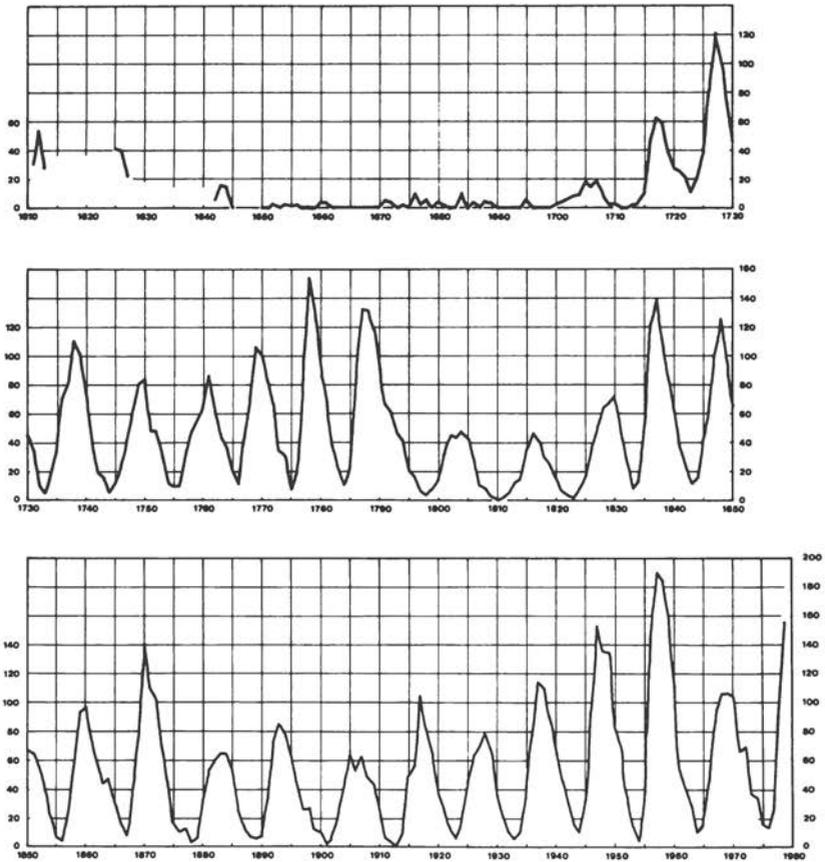


FIGURE 1.2 Sunspot cycle, A.D. 1610–1979, as represented by the annual mean sunspot number for those years. (Courtesy of J. A. Eddy, High Altitude Observatory, NCAR.) The interval of about seven decades beginning in 1645 when sunspot numbers were unusually low is known as the “Maunder Minimum,” which coincided with a significant drop in global temperatures. The sunspot records between 1610, when Galileo used a telescope, and 1640 are mostly too scanty to reconstruct with confidence.

a localized region may flash to temperatures of tens of millions of degrees, accompanied by a great burst of x rays and energetic particles. The flash of ionizing radiation creates an absorbing layer deep in the earth’s ionosphere that completely blacks out shortwave radio communications.

Spectacular instances of charged-particle emission from the sun accompany large changes in the sun’s local magnetic field that occur during the first

few minutes of flare eruptions. These energetic particles are easily detected in the earth's magnetosphere and down through ionospheric levels. Their transit time from the sun to earth ranges from minutes to hours. On the occasion of very great solar flares, those that occur on the average once or twice in an 11-year solar cycle, protons with energies of billions of electron volts appear all the way down to the surface of the earth.

A less dramatic emission of charged particles from the sun, yet having greater importance for the solar-terrestrial connection, is the solar wind. A hot plasma, that is, an ionized gas composed of an equal number of ions and electrons, forms the outer atmosphere of the sun, the corona. It is not contained by solar gravity but flows away from the sun and escapes. This outward flow gives rise to an unceasing wind of solar plasma that streams past the earth and out toward interstellar space.

There is evidence that our star undergoes changes that are important to the human environment. It is now established that small variations of the total solar luminosity occur from day to day as dark sunspots and bright plages rotate across the solar disk. Numerical models indicate that variations of the same amplitude as these short-term variations but sustained over much longer times could be of importance to climate dynamics. There are also valid theoretical reasons to believe that variations of total radiative output of this magnitude might be connected with the 11-year solar magnetic variations and with the changes in their amplitude over centuries.

Thus, our past perception of the sun as a quasi-static object slowly burning its hydrogen to provide a constant flux of heat and light has been altered dramatically by recent advances in solar research, both from the ground and from space. Instead, there is increasing evidence that these are subtle but possibly predictable changes in the sun that may be important to the human environment.

2. The Interplanetary Medium

Our understanding of the interplanetary medium has undergone considerable modification in recent decades. Before the 1950's it was generally believed that the mechanism by which solar variability affects the earth's atmosphere was primarily photoionization, which created the ionosphere, and sporadic streams of charged particles, which produced magnetic storms and auroras. Solar magnetic fields appeared to bind the coronal plasma tightly to the photosphere, and the earth's magnetic field served to confine the ionized component of the earth's own atmosphere. Interplanetary space was thought to be almost empty.

According to modern hydrodynamic theory, the solar wind flows from the lower corona, and the velocity steadily increases up to about 400 km/sec at

about 20 solar radii. Although parameters fluctuate in time and space, with certain geophysical consequences, it is now well established that the solar wind is supersonic throughout the interplanetary medium. It transports away from the sun about ten billionths of the energy that is emitted as light and other forms of electromagnetic radiation; but this particle flux, when disturbed, has terrestrial impacts of greatly magnified proportions. Beyond a few solar radii from the sun, the rarified plasma of the solar wind is nearly collision-free and electric currents may flow with almost negligible resistance. As a result, the solar magnetic field is "frozen" into the solar wind and is carried with it into interplanetary space.

At the same time as the solar magnetic field, thought to resemble that of a magnetic dipole (bar magnet) close in, is drawn outward by the solar wind, solar rotation bends the field lines that emerge from the solar surface into Archimedean spirals that extend as far as a shock front with the interstellar medium, described below. The field lines on opposite sides of the midplane of the heliosphere have opposite polarity, and the polarity of the whole system reverses at the beginning of each new 11-year cycle. (This is the 22-year "magnetic cycle.") Thus, the pre-1950 simplistic view of an essentially passive interplanetary space has been drastically revised.

When the normally quite smooth flow of the solar wind is made unusually turbulent (for example, by a passing shock front from solar-flare ejecta) the frozen-in field lines are tangled, and such relatively localized clumps of kinky field lines can scatter cosmic rays in random directions. These deflections of cosmic rays away from the midplane of the heliosphere and from the neighborhood of the earth are observed as temporary decreases in the cosmic-ray flux and are an indication of smaller-scale structures in the solar wind caused by transient solar activity.

The relative role in modulating cosmic-ray fluxes played by changes in the large-scale geometry of the heliospheric magnetic field during a solar cycle, variations in the smaller-scale structures, and changes due to the magnetic-field reversal in alternate cycles have yet to be assessed.

It is believed that eventually the solar wind is slowed to subsonic speed at a shock front far beyond the orbits of the minor planets, where it collides with the interplanetary gas. Outside the shock front, the subsonic and turbulent solar wind mixes with the interplanetary gas out to another boundary, outside of which the interstellar medium is undisturbed. This outer boundary is the "heliopause," and the volume contained within it is the "heliosphere." No space probe has reached either the inner shock front or the heliopause, but Pioneer 11 and Voyagers 1 and 2 may eventually accomplish those missions and report the position of those boundaries if their instruments survive the epic journey.

3. The Magnetosphere

As the solar wind flows from the sun, it transports the solar magnetic field lines outward through interplanetary space. The earth's intrinsic magnetic field presents an obstacle to this magnetized plasma flow, which is deflected by the earth's field and leaves a cavity shaped like a comet head and tail (Figure 1.1). The blunt upstream "nose" of the cavity is normally at about 10 earth radii (65,000 km) from the earth, and its tail stretches beyond the moon's orbit, perhaps as far as 1000 earth radii. This huge bag of plasma, the magnetosphere, contains charged particles with energies ranging from thermal energies to hundreds of millions of electron volts. Since the solar-wind flow is "supersonic," a shock wave signaling the impending obstacle stands in front of the magnetospheric cavity. (See Figure 1.3.)

As the solar wind impinges on the magnetospheric boundary, the interplanetary magnetic field embedded in it becomes connected with the field of the magnetosphere. In this magnetic merging (or reconnection, as it is called), some of the geomagnetic field lines are stripped from the magnetosphere and become open to interplanetary space in the geomagnetic tail. In the process, energy, momentum, and particles are transferred from the solar wind to the magnetosphere. The solar-wind plasma, blowing across the open field lines over the polar caps, constitutes a gigantic dynamo that can generate a voltage drop across the magnetosphere of up to 100,000 V, electric currents of 10^7 A, and 10^{12} W of power. The energy, momentum, and particle transfer are governed by such solar-wind parameters as speed and magnitude, as well as by the direction of the interplanetary magnetic field. But it is the ram pressure of the solar wind that shapes the actual size of the magnetospheric cavity; and as the ram pressure varies, the entire magnetosphere quivers in quasi-periodic oscillatory modes like a mass of jelly. This represents another possible mechanism of energy transfer from the solar wind to the magnetosphere; so does the "friction" of the solar-wind flow against the magnetopause.

The steady flow of the solar wind is responsible for the formation of well-defined regions in the magnetosphere (see Figure 1.2), and variations in the characteristics cause well-defined temporal patterns of response of the magnetosphere. One such basic response pattern is the "magnetospheric substorm," a sequence of events triggered when the magnetosphere becomes overloaded with energy from the solar wind. The most conspicuous manifestation of a substorm is the acceleration of particles from the plasma sheet (Figure 1.1); some of these particles are propelled along magnetic field lines and further accelerated toward the auroral zone, causing the visible aurora. Another part of the accelerated plasma is captured by the magnetic field and injected into the Van Allen radiation belts.

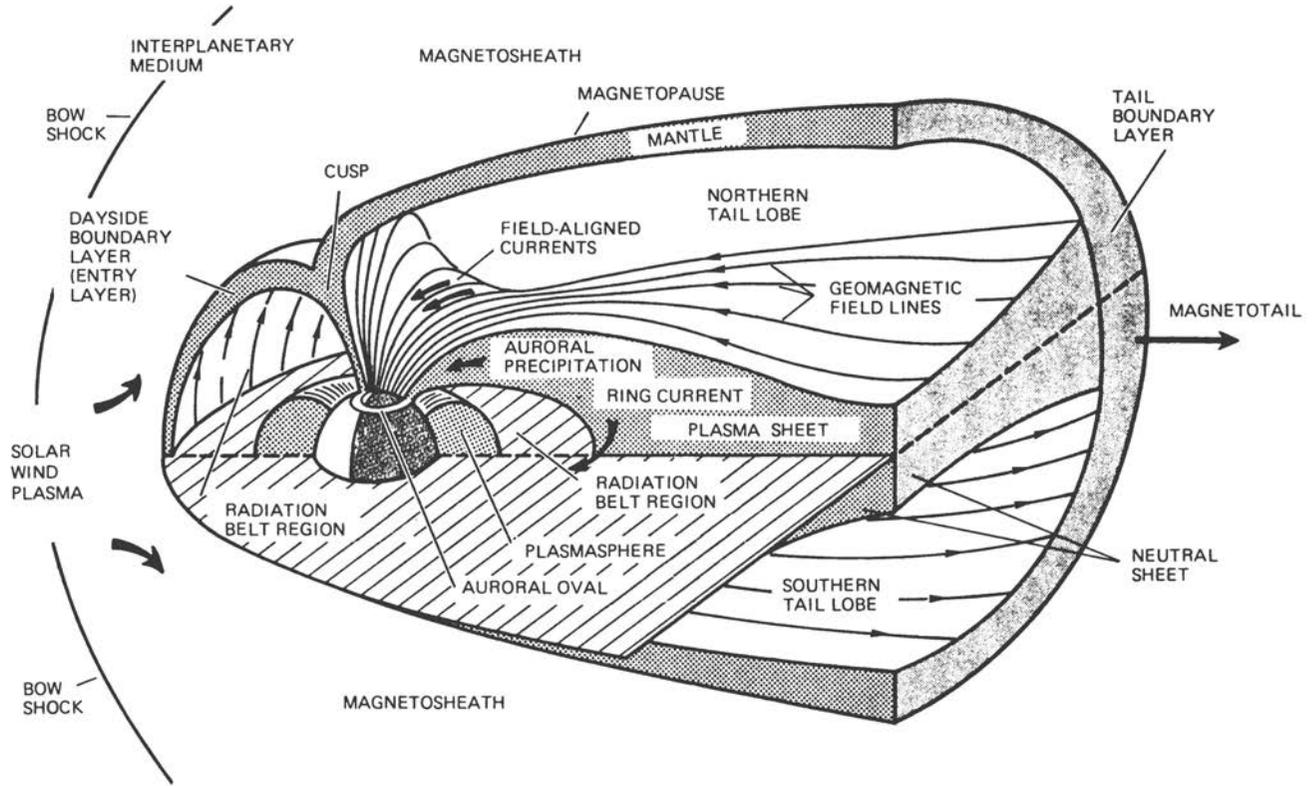


FIGURE 1.3 Schematic view of the magnetosphere, showing some of its major features. (Not to scale.) Terms in italics below refer to labeled items in the figure. The earth's magnetic field resists the entry of *solar-wind plasma* blowing from the left and carves out a comet-shaped cavity, the tail of which (*magnetotail*) is swept perhaps thousands of earth radii downstream (to the right). A collisionless *bow shock* upstream signals the presence of the magnetosphere. Between the bow shock and the *magnetopause* (the outer boundary of the magnetosphere proper) is the turbulent *magnetosheath*. Solar-wind particles are believed to be transferred into the magnetosphere in a number of ways, including transport into the *entry layer*, *cusp mantle*, and *tail boundary layer*. Their energy finds its way into the *plasma sheet*, which constitutes a reservoir for *auroral precipitation* into the ionosphere in elliptical bands around each magnetic pole known as *auroral ovals*. The field lines that are rooted in the polar caps and that are swept downstream to define the *tail lobes* are thought to be open to the interplanetary magnetic field in the distant magnetotail. The field lines in the plasma sheet are severely stretched and may be subject to reconnection at the neutral sheet, especially during geomagnetic substorms, thus consuming magnetic energy to accelerate plasma toward the earth into the *ring current* and the aurora. The field lines in the *radiation belt region* and defining its outer surface are closed and become less and less distorted with decreasing height above the earth. The radiation belts enclose and overlap with the *plasmasphere*, in which the plasma is cooler and denser than the energetic radiation-belt plasma. The plasmasphere may be considered an outward extension of the ionosphere. (Courtesy of J. G. Roederer, Geophysical Institute, University of Alaska.)

A more violent response is elicited when a blast wave generated by a large solar flare hits the magnetopause; the sudden compression increases the geomagnetic-field strength all the way to the surface of the earth and shakes up the entire particle population. Some energetic particles are dumped into the atmosphere in the auroral oval, others are captured to create a large equatorial ring current of millions of amperes at a distance of 3-4 earth radii. This sequence of events characterizes a "sudden commencement magnetic storm," a phenomenon that has been known for over a hundred years.

In addition to the storage, transfer, and acceleration of particles, a veritable concert of waves is created on the surface of and inside the magnetospheric cavity. For instance, some recent results have shown the magnetopause to be continually in motion, with waves excited there and probably propagating toward the magnetotail. This process also transfers energy from the solar wind to the magnetosphere. Other waves, like whistlers, deflect trapped particles from their trajectories and precipitate them, thus converting organized energy into disorganized energy, or heat. Such microphysical processes are beginning to be known and understood; but they now need to be put into the larger-scale picture of energy transfer from the solar wind into the magnetosphere and the transport of energy throughout the magnetosphere/ionosphere system. There are some novel suggestions about the nature of possible energy transfer and transport processes, but quantitative *in situ* measurements to define the actual mechanisms remain to be made.

Since each point of the magnetosphere is physically linked to the upper atmosphere by a magnetic field line, the ionosphere has an important effect on the magnetosphere, and vice versa. The coupling between magnetosphere and ionosphere is effected by a complex system of electric currents flowing along magnetic field lines between the two regions. Through this current system, electromagnetic energy is drawn from the magnetosphere and dissipated in the form of heat in the electrically resistive ionosphere. The high-latitude regions play a particularly important role in this process of energy deposition in the solar-terrestrial system.

Research in the magnetospheric/ionospheric environment is currently exploring the fundamental unifying concept of an electrodynamic system connecting the atmosphere/ionosphere/magnetosphere. The development of this unified view will characterize the main objective of future work in the near-earth space-plasma environment. Already some evidence exists for the influence of atmospheric electrical and dynamical processes on the ionosphere and magnetosphere; the evidence for possible inverse influences, however, so far has remained rather elusive.

4. The Ionosphere

Although the ionosphere may be considered a part of the magnetosphere (and these are treated as a unitary entity in this study), its behavior is primarily powered by the diurnal cycle of solar electromagnetic radiation, especially in the ultraviolet and x-ray bands of the spectrum, and, at high latitudes, by the dissipation of energy from the magnetosphere. The existence of the ionosphere was first demonstrated by Marconi's trans-Atlantic radio experiments in 1901, and its height was measured in 1925. Later, distinct layers were identified, associated with the altitude profile of the electron density in the ionosphere (Figure 1.4).

At high levels (>250 km) ionospheric winds of over 100 m/sec are set up by the diurnal heating and cooling of the thermosphere. These tend to blow in great-circle paths away from the most heated part of the atmosphere (near midafternoon at the subsolar latitude) to the coldest part on the nightside. The winds drive the ionization down the field lines to lower altitudes by day and raise it by night, which helps to maintain the F-layer ionization density during darkness.

At high latitudes very large magnetospheric electric fields (tens of millivolts/meter) are impressed on the ionosphere and are capable of causing the F-layer to move horizontally with speeds as high as 1 km/sec. The local F-region electron density at such latitudes thus depends on the time history of the region and when it was last in sunlight. A large region of low electron density (the "trough") is found on the nightside, poleward of which are large irregular density increases produced by precipitating energetic particles.

Whenever there are strong electric fields in a plasma, one or more plasma instabilities may occur. In the F-region, such instabilities seem to be present regularly at high latitudes and over the equator at night. They create local fluctuations in electron density with a wide range of scales. These irregularities produce multiple echoes, strong scintillation, and fading on radio frequencies up to several gigahertz, including those used by communication satellites, which were originally expected to provide trouble-free communications.

In the lowest part of the ionosphere, the D- and E-regions at 70-150 km, upward propagating tides can create layers of intense ionization that move vertically in time. The patches of ionization produced in this way are known as "sporadic E" and can cause the high-frequency signals to be reflected up to 2000 km from the source on a single hop. In summer, sporadic E is the cause of severe interference on TV broadcasts.

During geomagnetically disturbed times, precipitating particles and electric currents deposit large amounts of energy at high latitudes, and the resulting

ATMOSPHERE

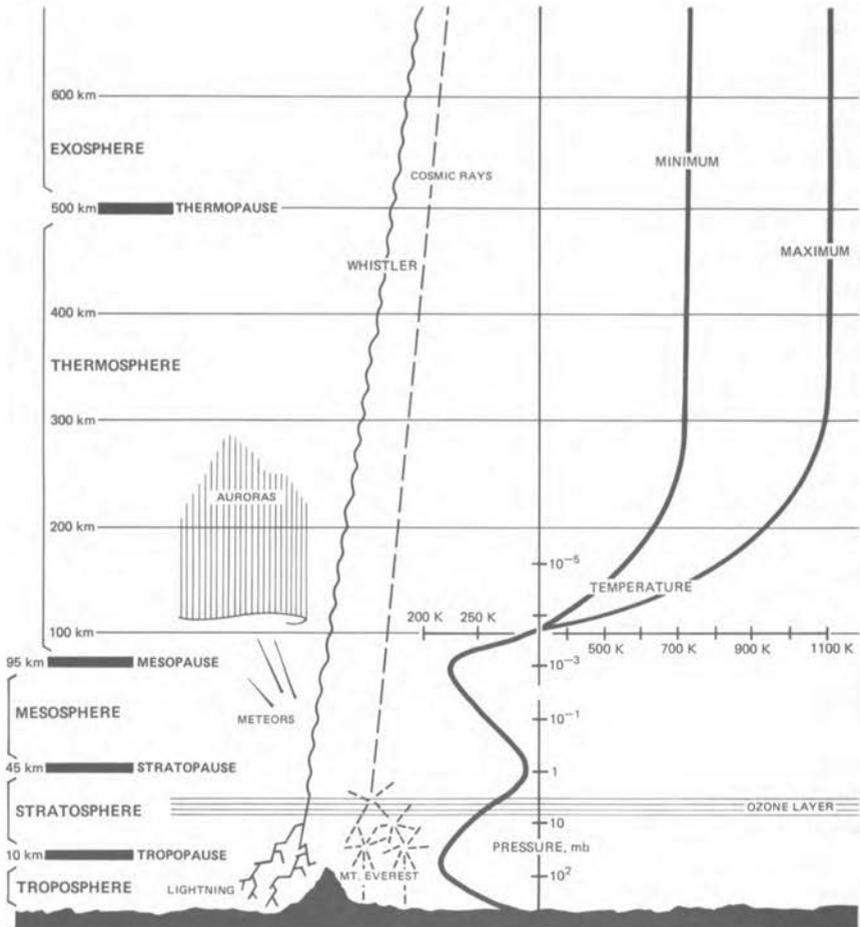
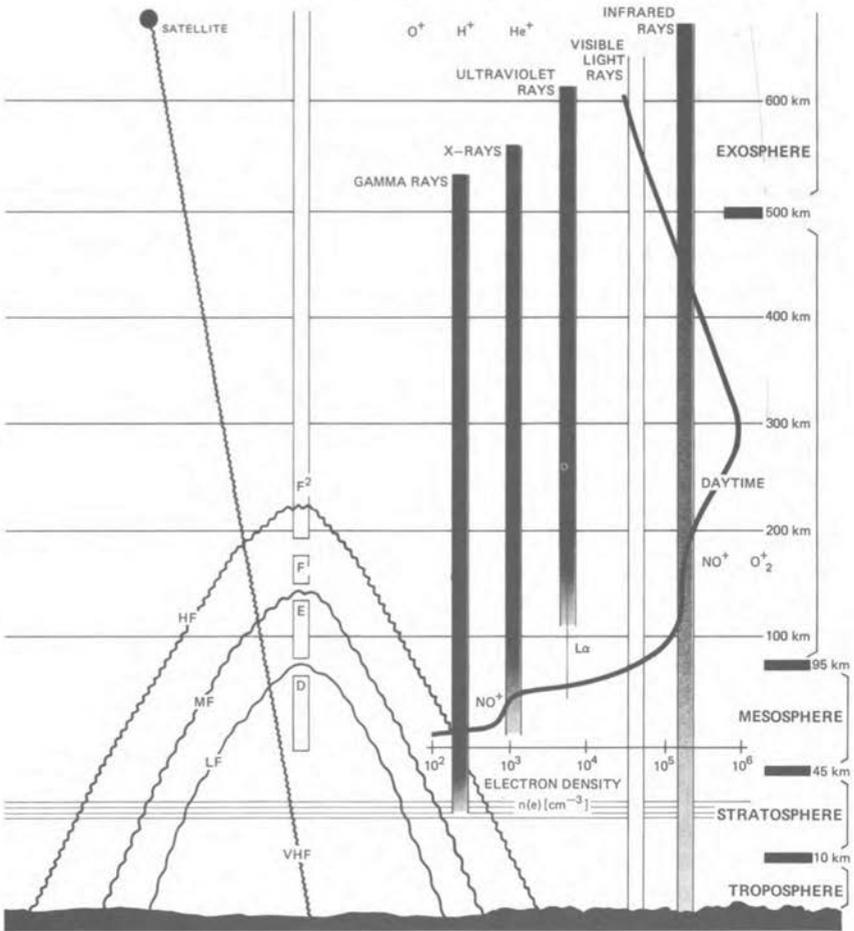


FIGURE 1.4 Ionized component of the atmosphere is produced by cosmic rays, gamma rays, x rays, and ultraviolet rays, which have maximum ionization rates in the D, E, F1, and F2 regions. Maximum concentration of electrons occurs in the F2 region, where the ionized component is about 1/1000 of the neutral-particle density. Shortwave radio signals are reflected from the ionosphere. X rays from solar flares produce radio blackout at an altitude of 60 to 75 km. Microwaves penetrate the ionosphere for satellite communica-

IONOSPHERE



tions. Temperature inversions define the tropopause, stratopause, and mesopause. The atmosphere is mixed, and the composition of major constituents is essentially constant up to the mesopause. Ozone concentrates in a thin layer in the stratosphere. At higher levels, molecules dissociate and lighter elements separate out by diffusion. Temperatures in the thermosphere maximize at sunspot maximum.

excess heating can completely change the global pattern of winds in the thermosphere. Large equatorward winds are established on the nightside, and large-amplitude gravity waves also are generated, which help to transport energy to lower latitudes; both of these modify the ionosphere on a world-wide scale.

5. The Neutral Atmosphere

The ionosphere, or ionized constituent of the atmosphere, was alluded to above, but it is the *neutral atmosphere* that constitutes the major component of the atmosphere for the lowest few thousand kilometers, until it is eventually dominated by the ionosphere. The pressure and density both steadily decrease with height, but the temperature-height curve follows a pattern of its own determined by the local balance between heating and cooling. The resulting temperature profile provides a natural basis for defining a series of successive regions (concentric spherical shells), as shown in Figure 1.4. Beginning at the earth's surface, these regions are: the troposphere ("changing" or "overturning" sphere), stratosphere ("settled" sphere), mesosphere ("middle" sphere), thermosphere ("hot" sphere), and exosphere ("outside" sphere). The stratosphere and mesosphere, which have much in common, are often considered as a unit, called the middle atmosphere.

In the solar-terrestrial system, the *neutral* atmosphere is the ultimate repository for most of the energy emitted by the sun and reaching the earth and its immediate environment. An average of about one third of the incident sunlight is reflected or scattered back into space by the earth's atmosphere, cloud cover, and surface; most of the remaining two thirds is absorbed by the earth's surface, including those huge reservoirs of heat, the oceans. The surface emits infrared radiation, which heats the troposphere. The actual temperature of a body of air is determined by the balance between heat gained and heat lost, as modified by being transported from one place to another—horizontally by the motion of air masses and winds, vertically by convection. These motions, in turn modified by the earth's rotation, are the atmosphere's response to imbalances in pressure; thus thermal radiation and atmospheric transport govern the distribution of the available energy in the troposphere and thereby generate our weather and climate.

Society is naturally more interested in this readily apparent aspect of solar-terrestrial relations than in its more esoteric aspects. Seeking to answer questions about the effect of fossil-fuel combustion in the industrial nations or of slash burning in tropical forests on the carbon dioxide burden and the resultant long-term change in atmospheric temperature, or similar questions about the possible effects of solar variability, is of obvious practical importance.

In the early 1970's it was realized that deposition in the stratosphere of products of high-temperature combustion, such as nitrogen oxides and water vapor by large fleets of supersonic transport aircraft, might cause a serious reduction in the abundance of stratospheric ozone. Recently, there has been increased recognition that even in the troposphere, where radiation and dynamics were once thought to be the dominant factors in controlling the environment, photochemistry is also important.

Experimental and observational platforms for use in the region from about 40 to 100 km are few in number and limited in capability. Instruments carried on small rockets and on balloons and parachutes dropped from balloons have been used for exploring the stratosphere. Rocketborne instruments have successfully attacked the lower and upper thermosphere. Satellite systems, such as the Atmosphere Explorer series, have been spectacularly successful in providing detailed information about the thermosphere above about 135 km. Ground-based sounders, such as incoherent-scatter radar, have also provided invaluable information in this region. By contrast, the upper part of the middle atmosphere remains poorly explored and poorly understood.

Our developing understanding of the neutral atmosphere from the surface of the earth to the exosphere is an excellent example of the synergistic interplay of basic research and applications. The need to understand the atmosphere in order to apply such knowledge to the challenges facing society has sometimes driven the discipline, but atmospheric science studies, even those of the atmospheres of Mars and Venus, have provided the experimental techniques and theoretical understanding needed to solve complex problems in terrestrial atmospheric science when suddenly and unexpectedly the need to solve them became urgent. It is greatly to our advantage to continue to explore the atmosphere, using as our methods the entire range from the most basic kind of research to the most direct of applications.

6. Practical Impacts of Solar-Terrestrial Relationships

In recent years, a variety of events has brought home to the general public a sense of the practical consequences of solar-terrestrial relationships. Perhaps the most dramatic experience was the plunge to earth of Skylab. It became a media event with all the ingredients of suspense and potential for catastrophe to frighten a confused public. When the last astronaut left Skylab in 1974, it was thought that the spacecraft was in a safe parking-orbit, where it could await a visit by an early Space Shuttle flight, which would push it to a higher orbit for safekeeping until it could be refurbished and reactivated. Unfortunately, the plan was frustrated by a delay in the Space Shuttle schedule and by the rapid rise of solar activity toward sunspot maximum. With high sun-

spot activity came a hotter and denser atmosphere at Skylab altitude, which increased the drag on Skylab and caused the orbit to decay much faster than anticipated. Skylab thus fell victim to solar activity. Our inability to predict where it would fall exemplifies our current lack of instruments to observe with adequate precision the solar output of extreme ultraviolet and x rays, which control the density of the atmosphere at satellite altitudes.

Discussed in some detail in Part II, Chapter 6, are four areas in which research in solar-terrestrial relationships can clarify important impacts on society and technology: (1) predictions about the space environment; (2) stratospheric ozone—a feedback loop between the biosphere and solar-terrestrial research; (3) ionospheric physics and radio communication; and (4) the potential connection between solar variability, weather, and climate. Several important recommendations to guide future research on the solar-variability-weather-climate question have been formulated in a separate study that is cited in the Appendix.

2

Principal Recommendations

I. SCIENTIFIC RECOMMENDATIONS

A unifying theme connecting the elements of the solar-terrestrial system is the importance of coupling processes in the large scheme of energy transfer from the sun to the troposphere. The connections throughout the system are difficult to appreciate when studies are confined to individual elements of the system. The present report focuses attention on interactive processes within the system and recommends observational and theoretical programs that will lead to significantly better understanding of the interrelationships. Some of the interactions that span widely separated elements of the system may have profound influences on major features of the behavior of a specific regime. Other couplings may be so sensitive to even small variability in a variety of physical, chemical, and dynamic factors that the impacts of variability may become greatly amplified.

The general recommendations that follow below were arrived at from detailed considerations of the complex interaction processes in the solar-terrestrial chain. A brief statement of the scientific rationale accompanies each recommendation. A fuller background discussion is contained in appropriate sections of Part II.

The eight scientific recommendations given below are to be treated as a single unified set. The removal of any individual recommendation would result in a weakening of the interconnected chain. *Thus, the order in which the recommendations are given implies nothing about their relative priority.* Instead, the sequence starts with the energy source (the sun), continues with the transmission line (the interplanetary medium), and ends with the sink

(the magnetosphere-ionosphere-atmosphere system). The set of recommendations is intended to be a basic prescription for a broad-based program to study this entire coupled system and to assure that already planned programs and missions will be better integrated. It is also essential that this set of recommendations be considered in the context of a number of recent Academy studies, in particular, *Solar-System Space Physics in the 1980's: A Research Strategy* (NAS, Washington, D.C., 1980), a report of the Space Science Board's Committee on Solar and Space Physics, and *Upper Atmosphere Research in the 1980's: Ground-Based, Airborne, and Rocket Techniques* (NAS, Washington, D.C., 1979), the report of a study conducted under the auspices of the Committee on Solar-Terrestrial Research. The recommendations of these and other relevant reports are given in Appendix A.

1. The Solar Radiative Output

a. *We recommend the initiation of a long-term national program to study variations of solar luminosity and spectral irradiance.* The most direct link between the sun and the atmosphere of earth is the flow of radiative energy. Variations either in the total flux (solar constant) or in specific spectral components can bring about direct changes in atmospheric composition, circulation, or temperature.

b. *We recommend a broadly based program of theory and ground-based and spaceborne observations to understand the fundamental mechanisms of solar variability.* The sun is the starting point and source of energy of the solar-terrestrial system. The object of these efforts, as far as solar-terrestrial research is concerned, is to increase our basic understanding of the processes of energy generation and transfer within the sun and the processes responsible for solar activity. Ultimately such study could lead to a predictive theory of solar activity and the variable outputs of the sun, to replace the present largely statistical basis for forecasting.

2. Linkage between the Sun, the Interplanetary Medium, and the Magnetosphere

a. *We recommend observational and theoretical studies of physical processes responsible for quasi-steady interplanetary flows, solar-wind acceleration and dynamics, and the three-dimensional structure of the heliosphere.* These processes provide the connection between localized processes at the sun and the overall structure and dynamics of the solar wind, which then determines the basic structure and dynamics of the earth's magnetosphere and the power transferred into it.

b. *We recommend observational and theoretical studies of how transient events on the sun propagate into and through the interplanetary medium.* These phenomena are of fundamental importance to the physics of the solar wind and also provide the connection between solar transient events (flares, for example) and their concomitant terrestrial effects, such as magnetospheric storms and changes in thermospheric flow patterns. This recommendation includes support for optical, radio, and cosmic-ray monitoring of solar activity from the ground; *in situ* measurement of disturbances of solar origin; and theoretical studies of finite amplitude waves, shock waves, and current sheets and their interactions with charged particles.

c. *We recommend a coordinated program of observational and theoretical studies to determine how energy and momentum are transferred between the solar wind and magnetosphere, both for quasi-steady-state and transient conditions.* In this crucial area, understanding of basic physical processes of the magnetospheric boundary has improved. Major breakthroughs in understanding the mechanisms and processes of energy and momentum transfer across boundaries are now expected through combined ground-based and multi-spacecraft studies. A comprehensive and coordinated observational program, with a complementary theoretical effort, is required to accomplish these objectives. The posed energy and momentum transfer problem is a prototype for many interacting astrophysical plasma systems, and it is directly related to current problems under study in laboratory plasmas; thus, research findings from the recommended effort will have application to related problems in astrophysics and plasma physics.

3. Linkage between the Magnetosphere, Ionosphere, and Atmosphere

a. *We recommend a coordinated scientific effort to understand the magnetosphere-ionosphere-atmosphere energy-transfer processes in magnetic-field-line regions that pass through the auroral zone, the polar caps, and the geomagnetic tail.* This recommendation addresses the need for a deeper insight into the physical mechanisms governing the effect of entry of solar-wind plasma, hydromagnetic waves, and solar energetic particles into the magnetosphere-ionosphere system. The relevant regions—the cusps and the distant tail—have not been studied in detail by earlier programs such as the International Magnetospheric Study.

b. *We recommend a coordinated scientific effort to understand the global coupling of the magnetosphere-ionosphere-atmosphere system.* The ionosphere, far from being a passive “viewing screen” of magnetospheric processes, plays an active role as a major sink of magnetospheric energy, exerts important feedback effects on the magnetospheric regions to which it is

linked, and is the source of important perturbations that propagate to lower latitudes. In particular, energy and momentum input into the high-latitude ionosphere and atmosphere alters the global circulation and the temperature structure of the thermosphere that are established mainly by solar heating. On the other hand, changes in the basic circulation pattern, caused by auroral activity or upward propagating waves from the lower atmosphere and thunderstorm electrical fields, may influence electrodynamic processes in the ionosphere and the magnetosphere. Pursuit of this recommendation will thus require coordinated research on a global scale.

4. Linkage between the Sun and Elements of the Atmospheric System

a. *We recommend an effort to determine the effects on the chemistry and energetics of the middle atmosphere of both (i) exchange processes with the troposphere and thermosphere and (ii) solar variability.* The effects of the variability of both solar electromagnetic radiation and particle input on the structure of the middle atmosphere are poorly understood. Possible changes in chemical composition due to solar variability could perturb radiative and dynamic processes of the middle atmosphere, and this possibility needs to be explored. The middle atmosphere is also affected by exchange processes from below with the troposphere and above with the thermosphere that must be considered in any attempt to understand the middle atmosphere. Perturbations (e.g., to ozone concentrations) resulting from natural or human activity could affect the earth's climate.

Appendix A includes excerpts of recommendations from several recent studies that cover much common scientific ground. The above recommendations and those contained in the previous reports are mutually supportive and consistent. Taken together with the present recommendations, they provide a comprehensive plan for all aspects of solar-terrestrial research.

II. MANAGEMENT RECOMMENDATIONS

The study group also considered a number of issues that are of concern to, and affect all phases of, solar-terrestrial research. The background to those considerations is described in some detail in Chapter 3. The issues considered both cut across the specific disciplines and also involve the various government agencies responsible for carrying out and/or supporting research in this field.

No attempt has been made to assign relative priorities to the following recommendations, because they address different activities that are not di-

rectly in competition with each other. Although relative costs and cost-effectiveness often play a role in decision making, estimates of costs, besides being hard to arrive at, depend on how far each recommendation is developed. Furthermore, some of these recommendations either cost virtually nothing (for example, Recommendation II.1) or would involve using already available resources in a more effective way (for example, Recommendations II.2 and II.3). Finally, we believe that the implementation of all of these recommendations will, in any case, lead in the long run to increased efficiency in the conduct of solar-terrestrial research and a lowering of costs.

1. Interagency Coordination

We recommend that national programs of solar-terrestrial research (STR) be coordinated among the interested federal agencies. The national efforts in STR are currently conducted by many agencies including the National Science Foundation, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Department of Energy, the Department of Transportation, and the Department of Defense. In a number of programs, such as the International Magnetospheric Study (IMS) and the Climatic Impact Assessment Program, lead agencies were designated to oversee the creation of a national plan and to coordinate the implementation of this plan. We believe that the cost-effectiveness of STR can be increased by establishing similar lead-agency responsibility for major components of the national program through a permanent interagency coordinating office.

2. Data Management

We recommend an organized program to facilitate the exchange, coordination, and dissemination of data from ground-based, suborbital, and spaceborne observations in STR. Better utilization of observational information could be accomplished by the implementation of a coherent national data-management plan. Such a plan must devise ways to analyze the data obtained from coordinated ground-based, suborbital, and space observations more efficiently and rapidly and to make these data readily available to the scientific community. The upgrading of existing facilities and/or the formation of a new center for the storage, retrieval, and analysis of STR data are necessary. The complexity and diversity of the numerous data sets that properly constitute the STR data base require innovative management and a truly dedicated effort to provide adequately for their handling. An intrinsic requirement is adequate funding for the continuity of effort at a level essential for realizing the full potential of the data. We commend recent NASA efforts for a pre-launch planning of data bases in several programs. More attention to support

of postmission data analysis is also required. We also note the importance of coordinating measurements from networks of spacecraft in order to facilitate study of spatial and temporal variations of phenomena.

3. Continuity of Synoptic Observations

We recommend a dedicated effort to support long-term synoptic observations of certain key parameters needed for the detection of trends in solar-terrestrial phenomena. There is growing evidence that long-term variations may take place in the state of the sun and its emissions. Continuing accurate observations are needed to monitor such trends in the solar constant and flux at UV, EUV, and x-ray wavelengths. Also, the systematic recording of many terrestrial variables on a global scale is essential to the empirical study of solar-terrestrial phenomena, as this provides a means of uncovering subtle linkages having no obvious chain of cause and effect. Among these variables are the properties of the solar wind and its embedded magnetic field, as well as indices of geomagnetic activity. We believe that these requirements can best be fulfilled if special cognizances and long-term commitments are accepted by individual agencies.

4. Support for Theory

We recommend improved support for both theoretical studies and retrospective analyses of existing data. Historically the emphasis in STR has been focused on empirical studies based on newly acquired data. As STR matures, the need for theoretical work and modeling grows; an appropriately balanced program must provide for such effort. Theory not only codifies the understanding that has been gained but poses questions that help to shape future observational efforts. Similarly, the program must provide for the optimum use of data already at hand.

5. Innovation in Instrumentation

We recommend increased support for innovation in the development of instrumentation. To benefit from our enhanced scientific understanding in STR, the technology needed for new measurements must be updated. A program of dedicated support for research and development on new methods and techniques in STR is essential to the future health of a national program. This requirement is consistent with widely expressed concerns about obsolescence of scientific instrumentation in all fields of U.S. science.

3

General Considerations Affecting Solar-Terrestrial Research in the United States

I. INTERAGENCY COORDINATION IN MISSION PLANNING, SYNOPTIC OBSERVATIONS, AND FORMULATION OF A NATIONAL DATA-MANAGEMENT PLAN

Many of the major spaceflight missions and ground-based facilities planned for the future for solar-terrestrial research will have the character of national observatories. These programs will involve significant capital commitments by a number of federal agencies; good interagency planning is therefore essential to maximize the scientific returns. Since the planning and execution of large observational programs is usually a lengthy process, long-term commitments are necessary from both the scientific community and the funding agencies. *National interagency coordination is necessary* to ensure a proper mix between spaceborne and ground-based observations, as well as a good balance between theory and experiment. Experience has shown that efforts to broaden the observational base and the interactive participation of qualified scientists results in an important increase in scientific output from a given program for only small incremental financial support. The collection, archiving, and wide distribution of scientific data from a large variety of sources and over long periods of time has played an important role in advancing the field of solar-terrestrial research. However, the continuity of long-term observing programs tends to be given low priority by the science agencies concerned. *This work is so important for the long-range health of the field that a focused and well-planned national program must assure the long-term commitment needed for these observations.*

We are concerned that past efforts have invariably fallen far short of satisfying the requirements for precision and long-term continuity of observation. A higher degree of dedication to this kind of effort has to be encouraged. These requirements can best be fulfilled if special cognizance and long-term commitment are accepted by each individual agency. Where these observations are technically feasible by ground-based programs, it would seem appropriate to place responsibility with the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense, and the National Science Foundation, with close attention to possible international collaboration.

Long-term observations of solar spectral irradiance and solar-wind parameters are prime examples where there has been inadequate past commitment of resources and effort. Spectral irradiance monitoring has been recognized in the past as essential to ionospheric/magnetospheric research. However, these observations have been supported only in piecemeal fashion by various government agencies. There is no one agency dedicated to the support of long-term monitoring of this type, and no one agency has devoted sufficient resources or interest in this area to do it properly. Long-term, synoptic observations are often the only means of discovering linkages in the behavior of elements of the system, despite the absence of clear cause-and-effect relationships. The discovery of such linkage contributes greatly to the search for a better understanding.

Unprecedented amounts of scientific data have been accumulated from space missions, in part because many satellites have continued to function long after their designated prime mission phases. *Data handling and management* have become a problem because of the staggering amounts of data produced and the ever-evolving needs for conducting multiparameter studies. Planning efforts during several recent missions have given careful consideration to the difficulties, and the trend has been toward requiring experimenters to meet specified data-management conditions designed to speed up the data reduction time, to use common physical units and data formats, and to render the data base available to the scientific community rapidly in usable form. Objectives to be met include the provision of immediate and remote access to the data by principal investigators and their teams during a mission, similar remote access by the scientific community at large as soon as proprietary requirements have been fulfilled, and timely and automatic acquisition of the data by the National Space Science Data Center in order to satisfy all archiving requirements and the future needs of the entire scientific community.

Data gathering during the International Magnetospheric Study (IMS) was conducted in the four-year period 1976-1979. Coordinated ground-based,

atmospheric, and space observations took place during the IMS on an unprecedented scale. A major accomplishment of the IMS has been the near-real-time availability through the Data Acquisition and Display System of the Space Environment Laboratory of data obtained from an extensive array of ground-based magnetometers and the prompt deposition of the tapes in World Data Center A for Solar-Terrestrial Physics (both at NOAA, Boulder). This successful experience in data handling and management should provide guidance in developments that must take place throughout the space program in the next decade.

II. INTERNATIONAL COORDINATION

Past international geophysical programs—the International Geophysical Year and the International Years of the Quiet Sun, and more recently the IMS and the Solar Maximum Year—have been effective in stimulating activity at the international level. *International cooperation and information exchange* may be organized by (1) nongovernmental organizations, i.e., the Scientific Unions and Committees of ICSU; (2) intergovernment organizations, such as the World Meteorological Organization and UNESCO; and (3) bilateral or multilateral agreements between a national agency and equivalent organizations in the other country or countries.

The future development of STR programs in the United States will continue to be strongly dependent on the effectiveness of international cooperation and information exchange. In view of this fact it would be in the national interest to examine critically the present state of international cooperation and information exchange in all three levels mentioned above, to appraise the effectiveness of the responsible organizations in furthering the advancement of the field, and to evaluate the cost-benefits ratio and intellectual benefits of U.S. investments in international scientific cooperation and exchange in STR. Based on the outcome of such analysis, appropriate adjustments or changes in U.S. participation should be proposed where warranted.

III. THE ROLE OF THEORY

Theory and computer modeling must play a more fundamental role in the future development of solar-terrestrial research. This need is widely accepted and recognized, as evidenced by recommendations made in recent reports*

**Space Plasma Physics: The Study of Solar-System Plasma*, Volume 1, National Academy of Sciences, Washington, D.C., 1978. *Report of the Solar Terrestrial Theory Panel to the Solar Terrestrial Division of the Office of Space Science*, NASA, September 1978. See Appendix A.

and by the national commitment to the Post-IMS Data Analysis Phase. Theory can play a crucial role in identifying what key observations need to be made in order to establish a correct understanding of the processes at work. In addition to basic theoretical studies of an analytical nature, important contributions to the development of solar-terrestrial research will come through computer modeling and simulation. These efforts will parallel developments in meteorology, where local and global atmospheric models have provided important direction to the field. Computers have become essential because the complexity of the basic equations (which results from the large number of nonlinearly coupled independent variables) precludes analytical solutions. In solar-terrestrial research, the basic equations are often even more complex because additional couplings and nonlinearities are introduced by electromagnetic variables that are not present in the neutral, lower atmosphere. Computer models are useful for simulating large systems, for testing the importance of competing coupling processes on a global scale, and for providing a framework within which large amounts of data may be organized.

In the next decade computer modeling in solar-terrestrial research should achieve the status it has established in many other fields of physics. This will require the adoption of the latest numerical techniques and the state-of-the-art utilization of computers, particularly in interactive modes of operation. Seminars and workshops will help the training process.

The role of theory in solar-terrestrial research in the 1980's is discussed in greater detail in Chapter 4.

IV. NEW INITIATIVES AND INNOVATION

Initiatives in new directions on a modest scale ought to receive sympathetic consideration. One cannot foresee the discoveries that may come from innovative approaches. In the past, such opportunities have chiefly been provided through rocket and balloon programs. These and other methods for encouraging innovation need to be continued. For example, the Solar Terrestrial Division of NASA has recently introduced a "Space Science Notice for Solar-Terrestrial Theory Program." We would like to see similar investments by the other agencies, as well as notices for innovation in the development of instrumentation.

In addition, we hope that the Shuttle can be utilized to accommodate new instrumentation in a more effective way than in the past. Proponents of the Shuttle promised benefits in the form of the support of a wide range of sciences, which would expand the community of users and provide opportunities for innovations at low cost. It is essential to the health of solar-terrestrial research that these promises be fulfilled.

V. THE SOLAR-TERRESTRIAL RESEARCH COMMUNITY

Solar-terrestrial research has grown up as a hybrid field and now includes practitioners who came from a wide variety of more or less independent disciplines ranging from solar activity, geomagnetism, ionospheric studies, and aeronomy to theoretical plasma physics, laboratory chemistry, and nuclear physics. All have contributed to the field some of the thoughts and insights from their respective disciplines, and the synthesis of these contributions has provided the structure for a set of closely coupled studies that has come to be known as solar-terrestrial research. This research applies to a system that is vast and complex, not only in its sheer physical dimensions but in its all-encompassing range of processes and of scale sizes over which these processes operate. At one end of the scale, the orbit of the earth around the sun is determined by the long-range gravitational force that pervades the entire system, and at the opposite end, the composition of the atmosphere is determined by processes that take place on the atomic scale.

While the hybrid and wide-ranging nature of the subject and the diverse backgrounds of the individual scientists have led to a fertilization of the field on many fronts simultaneously, the problem of cross-fertilization among the specific disciplines or subdisciplines is becoming more and more important as our knowledge expands and the highly interactive nature of the system becomes evident. Most of the scientists who have made important contributions to solar-terrestrial research have retained a basic loyalty to what they regard as their own disciplines. The solar physicists who measure the extreme ultraviolet output of the sun tend to be motivated by their interest in what the measurements tell them about the sun rather than by the fact that the same radiation is largely forming the earth's ionosphere. At the other end of the chain, the chemists who determine the rates of catalytic reactions tend to be motivated more by their interest in chemical reactions than by the fact that the particular reaction under study might be an important sink for stratospheric ozone. In part, this is a sociological phenomenon that is probably unavoidable, since scientists are human beings who react to peer pressures and who seek established niches for themselves among the scientific groupings that have developed. Such tendencies can be counteracted, however, by *giving increased emphasis to solar-terrestrial research as a unitary discipline both within the academic community and at the science-policy level*. The creation of a more closely knit group of scientists who identify themselves as "solar-terrestrial scientists," rather than as "solar astronomers" or "atmospheric chemists," for example, will be a major step toward breaking down the barriers that currently exist and should help to bridge the gaps that lie between many of the older and better established specific disciplines.

The practical benefits flowing from a national program of solar-terrestrial research affect a broad range of technological endeavors as well as our

understanding of the potential consequences of the variability of the space and atmospheric environment. In the last two decades we have become heavily dependent on space-based communications, space-based meteorological satellites, and space-based defense systems. Both the design and operation of these systems, as well as their ground-based counterparts, draw on the knowledge developed by solar-terrestrial research.

We have also begun to appreciate the potential biological and climatic effects of subtle changes in solar luminosity as well as the potential capacity of human activities to disturb our environment. In each of these instances the products of solar-terrestrial research have contributed (and can be expected to contribute with increasing effectiveness) to the development of national policies as well as to the technical implementation of policy decisions.

4

Implementation Goals for the 1980's

I. INTRODUCTION

Scientific recommendations for the pursuit of solar-terrestrial research were presented in Chapter 2, Principal Recommendations (Section I). The scientific background for these recommendations is elaborated on in Chapter 5. We consider here the implementation of these recommendations.

This plan for the implementation of the recommendations is divided into two main sections, dealing, respectively, with theory as it affects the entire field and with the observational and theoretical goals specifically appropriate to each discipline. A fundamental goal in each instance is the attainment of "closure" in problem areas covered by the scientific objectives. By this we mean that experiment and theory should confront the same problems and ultimately provide identical solutions. Only in this way can it be claimed that scientific understanding has been achieved.*

II. THEORY

Because theory is an essential element in all areas of solar-terrestrial research, some general observations about its role in the entire field will be made here. We believe that additional emphasis on theory is warranted and that, in the

*This point was also emphasized in the report *Space Plasma Physics: The Study of Solar-System Plasmas*, Vol. 1, National Academy of Sciences, Washington, D.C., 1978. Its principal recommendations are reproduced in Appendix A.

past, theory has not received the level of support appropriate to its importance in solar-terrestrial research. The Study Committee on Space Plasma Physics (commonly known as the "Colgate Committee"), appointed by the Space Science Board, concluded that "the theoretical component of space-plasma physics needs to be strengthened by increased support..." and recommended "strengthening theoretical solar-system plasma physics." In the following sections, specific steps are proposed to achieve a more vigorous theoretical component of solar-terrestrial research.

1. We propose a substantial increase in the level of effort in solar-terrestrial theory, particularly work that is not tied to mission support or to routine data analysis. While it is difficult to estimate the optimum balance between theory and observation, we believe that doubling the current level of theoretical activity would be appropriate. We note that in the magnetic-confinement fusion program, which has roughly the same total magnitude of effort and a degree of scientific challenge similar to that of solar-terrestrial research, the manpower devoted to theoretical research in the United States is approximately 300 scientists. The recommended expansion in solar-terrestrial theory should be accomplished in an orderly fashion over perhaps 5 to 10 years. The recent funding of a line item for solar-terrestrial theory for theoretical studies by the NASA former Solar Terrestrial Physics Division is an important first step in this direction.

2. We urge the creation of career opportunities for theorists in solar-terrestrial research as a means of attracting outstanding individuals to this field. The key to this recommendation is stable funding, which will encourage institutions (academic, industrial, or government) to establish permanent positions for theorists working in the field. We note that the recent formation of the NSF Theoretical Physics Institute and the Magnetic Fusion Theory Institute have resulted in commitments by universities of additional tenured faculty positions and applaud these steps. National laboratories and industrial research centers have the organizational flexibility to create career opportunities if sustained funding is available.

The above two recommendations are similar in spirit to those made in the "Report of the Solar Terrestrial Theory Panel to the Solar Terrestrial Division" of NASA. That Panel recognized that the theoretical effort was inadequate and suggested a number of specific steps to increase its level to bring additional scientists into the field and to coordinate this activity as a whole. These recommendations were solicited by NASA after funds in support of theoretical research were obtained in response to the Space Science Board study *Space Plasma Physics: The Study of Solar-System Plasmas*.

1. The Role and Organization of Theoretical Solar-Terrestrial Research

The goal of solar-terrestrial theory is to achieve quantitative physical understanding and to develop models of the important physical-chemical processes occurring in the sun-earth system. This goal implies an eventual predictive capability in which the phenomena can be anticipated on the basis of well-founded principles. It is only through a predictive capability that crucial experimental tests and further research can best be directed and observationally inaccessible questions can be dealt with.

Theoretical research is a key means of integrating the large body of information that has been collected in each of the various subdisciplines of solar-terrestrial research. Magnetic reconnection is an often-quoted example of a phenomenon that is believed to occur in many parts of the sun-earth system—in the solar magnetic field, in explosive solar flares, possibly at interplanetary current sheets, at the magnetopause, and in the geomagnetic tail. Here, a common theoretical problem is embodied in processes occurring in these vastly different regions and provides a meeting ground for scientists specializing in diverse areas of solar-terrestrial research as well as in laboratory plasma physics.

As solar-terrestrial theory matures, it is expected that numerical models will play an increasingly important role. It will, therefore, be necessary for solar-terrestrial scientists to develop a better appreciation for the capabilities and limitations of numerical models and the ability to construct and use them. Analytical efforts, however, continue to play an important role in attacking physical processes that have not yet been incorporated into the numerical models.

As an example of the complementary nature of these theoretical approaches, one can point to the study of stellar interiors, where numerical models are absolutely essential but to which analytic theory contributes important results. Solar-terrestrial theory will advance best with a mix of contributors. Large groups, small groups, and individuals can all play a role in constructing numerical models to test and improve our understanding of large-scale systems, as well as being sources of innovative and critical thinking about the behavior of particular components or processes.

The coupling of theory and observation provides mutual support for an overall growth in understanding. In the absence of experimental results theory can become unrealistic, yet it is important that theorists have a measure of independence from current mission requirements. Working in advance of observations, theory can offer new insights that may suggest new types of experiments. Theoretical estimates of heretofore unmeasured parameters are

also needed to optimize forthcoming experiments. Similarly, if experimentalists seek to measure only predicted effects, progress in unexpected directions can be limited.

Although the interpretation of data is often mentioned as an important task for theory, it is not necessarily one of its key functions. The principal responsibility of theorists is to point out new relationships, find unifying concepts, and suggest new experiments. The actual analysis and interpretation of data are best left to experimentalists, who are familiar with the limitations of the data.

There are several concrete organizational and policy steps that will augment the theoretical effort and enhance the scientific productivity of solar-terrestrial research.

1. Definition teams for space missions or ground-based facilities should continue to include theorists, whose role is to focus observational research on key questions.

2. Similarly, theorists should be included as Guest Investigators at observational facilities, including ground-based instruments supported by various agencies as well as the NASA spaceborne observatories.

3. In order to maximize the scientific return from numerical modeling, dissemination of computer codes should be strongly encouraged. The computer codes should be well documented and written in a standard computer language.

4. We likewise encourage the dissemination and archiving, where desirable, of numerical solar-terrestrial data in a manner that will allow wide accessibility. Only a small fraction of the acquired numerical data is analyzed and published. However, interest in these data may be generated by future research. The problems of storage and retrieval of different data sets have already been discussed in Chapter 3.

5. The increased development and use of large numerical models in solar-terrestrial research may have important implications with regard to existing computer facilities. At present, the computer facilities available to solar-terrestrial theorists seem adequate. However, in the late 1980's the lack of adequate computer facilities could seriously inhibit future modeling efforts. In the mid-1980's the solar-terrestrial community and the appropriate federal agencies should consider ways in which to improve and/or replace the existing computer facilities before they become obsolete.

2. Significant Problems in Solar-Terrestrial Research

The richness of solar-terrestrial observations presents a difficult challenge to theorists: Which problem should they work on? Problem selection requires

judgment and insight. Too often, theoretical effort is expended on explanations of (often striking) observations that are only a minor aspect of a more fundamental process. It is important to the productivity of solar-terrestrial theory that its limited human resources not be diverted to problems that are intriguing but that have little overall importance. Perhaps a theorist should ask, "How will solving this problem help to build a predictive capability?"

In every area of solar-terrestrial science there are many subjects for which research will build a predictive capability. The discussion that follows is intended to demonstrate this point by selected examples. It is by no means a complete list and should serve only as an indication of the type of research that a theory program should undertake. Other examples will be found in the discussion of each discipline below.

The issue of constancy of the so-called solar constant can be addressed by computer models of the solar convection zone. The questions to be answered include: What relationships exist between the solar diameter and the solar luminosity and spectral irradiance? Are there solar luminosity variations with amplitudes and time scales of climatological significance?

The interplay between solar plasma velocity and magnetic fields controls short-term solar variability. Processes leading to intensification, dissipation, or reconnection of magnetic fields are of prime importance and amenable to computerized studies. Initial work has been done in both solar physics and in allied fields such as fusion research. An accepted model of how convection influences the sunspot cycle is not yet available, and there are competing models (e.g., dynamos versus torsional oscillations). Theoretical work should attempt to identify distinguishing observational consequences of the various models. An understanding of heating and solar-wind acceleration in realistic magnetic geometries at high altitudes in the solar corona is needed, because these processes control the fluxes of solar-wind particles arriving at the earth.

Most of the variability in earth-solar wind interactions derives from changes in the solar-wind particle concentration and velocity and the orientation of the embedded magnetic field. Three-dimensional computer models with correct treatments of thermal conductivity, anisotropies, non-Maxwellian velocity distribution functions, and hybrid fluid/kinetic physics are needed as tools to examine the creation and propagation of solar-wind structures.

The magnetosphere-ionosphere system exhibits a wide variety of phenomena—collisionless shock, velocity shear layers, large-scale waves, neutral winds, and chemical reactions among both neutral and ionized species. The need is to study the individual processes in detail and to incorporate this knowledge into large-scale computer models of the magnetosphere. One such example is a study of "collisionless" viscosity at the magnetopause and its effects on plasma flow in the magnetosheath region. Detailed studies of

collisionless viscosity should be carried out with realistic representations of large-scale flows, since the choice of boundary conditions is critical. It is through this incorporation of microscale phenomena into the global-scale picture that magnetospheric physics can progress beyond the "cartoon" representation that has been prevalent for the last decade.

Energy input into the atmosphere from particles and ionospheric currents drives thermospheric circulation and causes changes in atmospheric chemistry. This area seems particularly important since chemical changes can affect both optical and infrared opacities, thus altering the earth's absorption and emission properties. Computer models, which are only just being constructed, will play a major role and must be coupled to advances in our knowledge of atmospheric chemical reactions.

If solar-terrestrial theory is to deal effectively with this vast array of problems, then the level of theoretical effort must be increased. This buildup should be accomplished by a steady and sustained increase over several years rather than by a sudden change in the support level. Abrupt buildups are rarely appropriate and successful only in fields where the problems have been well formulated and trained persons are already available. The recent theory initiative of NASA is an excellent first step toward this end.

If solar-terrestrial theoretical research remains at its present level, the 1980's will see some good scientific progress, but only in selected areas. The present program, even with the addition of the NASA theory program, simply does not have enough manpower to support a coordinated research effort in STR. In conclusion, it is perhaps well to remark that in any branch of science it is the advances in theory such as the codification of ideas, the formulation of unifying concepts, and the clarification of relationships that elevate the field from a descriptive subject to a quantitative science.

III. DISCIPLINE IMPLEMENTATION PLANS

The following sections differ considerably in length and in the detail of the discussions of observations and instrumentation. These differences must not be construed as implying a differentiation of priorities among the disciplines considered. Rather, they reflect the fact that for some disciplines we are able to refer to recent studies published by the National Academy of Sciences, whereas for others it has been necessary to incorporate details regarding proposed new programs and instrumental techniques not covered elsewhere.

Cross-references to the scientific recommendations are given where appropriate.

1. The Sun

The accomplishment of the scientific recommendations summarized in Chapter 2 requires that emphasis be given to selected areas of research in solar physics. To achieve the goal of long-term study of the solar constant and solar spectral irradiance (Recommendation I.1.a) will require a program to promote radiometer development and the improvement of radiation standards. Space Shuttle instruments and opportunities on other spacecraft need to be committed to this end, with assurance of their continuity as well as the initiation of dedicated, long-term programs that measure solar spectral irradiance from the ground. These ground-based efforts are an essential part of a realistic program for space, as a buffer against program interruptions or failures and as a scientific complement that can extend the range of solar parameters that are recorded.

Significant progress toward the goal of understanding solar activity and solar variability (Recommendation I.1.b) will depend on a number of different observational and theoretical efforts. These include the full utilization of the planned Solar Optical Telescope (SOT), with its ability to realize an order-of-magnitude improvement in spatial resolution over extended periods of time. This capability offers the possibility of resolving more of the detailed processes that produce sunspots and active regions that lead to the occurrence of solar flares. Advances of a different but equally important sort will come from observations of the global sun: of surface velocity fields and the extended magnetic fields that combine to produce the known cyclic behavior of solar activity and of conditions beneath the visible surface of the sun, where energy is transported and transformed and perhaps stored. Minute variations in the figure of the sun, if observed, can be related to changes in internal conditions and possibly to small changes in solar luminosity. The bounds of possible or expected solar variability can be identified by sampling the luminosity and spectral variations of other stars like the sun, i.e., through a program of monitoring a selection of nearby G, K, and M stars.

Progress in understanding solar variability relevant to solar-terrestrial research requires a theoretical attack on the various aspects of the solar gas dynamics and of the physics of the interior of the sun and the subsurface convection zone. As yet unsolved are questions regarding the coronal processes that lead to the production and modulation of the solar wind and the physical processes that produce solar flares. Continued effort is needed as well in recovering indices of the past history of the sun, utilizing natural, proxy indicators such as tree-ring radiocarbon and longer-lived isotopes such as beryllium-10 in sea and ice cores.

We stress that advances in the solar-physics aspects of a program in solar-terrestrial research will require emphasis on theoretical understanding and on

data reconstructions to complement a program of new observations. Observations, in turn, are needed from a program involving spacecraft, rockets, and modern ground observatories. A selected list is given below of needs in each of the areas that we believe constitute such a balanced program.

(a) *Ground-Based Observations*

(i) *Solar Luminosity and Spectral Irradiance* Programs to monitor the solar constant and solar spectral irradiance (Recommendation I.1.a) from outside the earth's atmosphere have been recommended in a number of recent national studies, and a new generation of measurements have now been initiated on spacecraft such as Nimbus 6 and Nimbus 7, the Solar Maximum Mission, and Spacelab. These techniques, if pursued for a long enough time, hold the promise of defining the limits of short-term variability in these important parameters. It is equally important to augment these studies with ground-based measurements to ensure continuity and to provide valuable auxiliary information. Some of the new techniques are described in the NOAA-sponsored study on "Monitoring the Solar Constant and Solar Ultraviolet." Indirect diagnostics such as measurements of time variations in the solar diameter, of the depths of central temperature-sensitive lines, and the photospheric limb-darkening distribution have been put forward as possibly fruitful methods. These ground-based techniques require investigation, since they may offer ways of following solar-luminosity variations at low cost from ground level over long time periods.

(ii) *Low-Velocity Facility* We recommend the development of several instruments at geographically separated sites to allow simultaneous measurements of mass circulatory movements on the surface of the sun (Recommendation I.1.b). The mapping of velocity fields on the sun's surface and the identification of patterns occurring before and during the emergence of active regions, will illuminate the dynamics of this process. Through the use of high spectral resolution and moderate spatial resolution, such instruments could sense small Doppler shifts from global-scale and smaller features. A design goal would be a velocity resolution of 1 m/sec, a spatial resolution of 5 sec of arc, and an ability to scan the disk of the sun once per hour.

(iii) *Oscillations and Secular Changes in the Solar Diameter* Measurements of oscillations in the figure of the sun provide a unique way of probing interior conditions that could lead to a better understanding of processes of energy generation, transmission, and storage (Recommendation I.1.a). An important step could be made through relatively straightforward upgrading and use of the existing Santa Catalina Laboratory for Experimental Relativity

by Astrometry (SCLERA) instrument at the University of Arizona and the development of several simple instruments to measure possible changes in the solar diameter and figure of the sun. Changes at the level of 0.005% (0.1 sec of arc) might be expected to accompany small changes in the solar luminosity; these could conceivably provide an auxiliary monitor of solar constant changes.

(iv) *Vector Magnetograph* Continued support should be provided for instruments to define vector magnetic fields in the solar photosphere and chromosphere (Recommendation I.1.b). Instruments with this capability now exist at NASA/Marshall Space Flight Center and Mees Solar Observatory in Hawaii. Almost all of our present understanding of solar magnetic fields is based on complex surface fields. The observational gap has particularly restricted our understanding of the physical nature of flare-producing regions. A vector magnetograph or Stokes polarimeter is currently envisaged as one of the focal-plane instruments to be carried on the SOT; to realize the full potential of this orbital instrument, at least one ground-based polarimeter should be supported.

The complexity of polarimetric analysis makes it imperative that the technique of observation and data reduction be developed carefully on the ground first (Recommendation II.5).

(v) *Global Magnetic and Velocity Fields* Careful study of global-scale velocity fields at, for instance, the Stanford Solar Observatory has yielded independent evidence for oscillations of the solar convection zone and deep interior, on the time scale of hours (Recommendation I.1.b). Sensitive measurements of the global-scale magnetic fields have yielded useful evidence on slow variations in large-scale magnetic structures, such as the extended areas of net unipolar field, associated with coronal holes. These measurements will continue to play an important role toward defining the basic mechanisms of solar variability.

(vi) *Neutrino Astronomy* Two areas of solar-terrestrial research can help to resolve the current dilemma of a surprisingly low neutrino flux from the sun. These are empirical and theoretical studies of relevant nuclear cross sections and neutrino lifetimes and continued development of second-generation neutrino detection devices capable of sensing low-energy neutrinos produced in the separate and independent steps of the solar nuclear-reaction chain (Recommendation I.1.a).

Detectors using gallium, lithium, thallium, and indium are now under study at the Brookhaven and Argonne National Laboratories and the Bell Laboratories. The present observational limit of a solar neutrino flux at least

three times smaller than expected theoretically raises questions with profound implications in many fields, including the possibility of secular changes in solar-energy production in the core of the sun. The present measurements have been extremely valuable in posing the problem. Yet the measurements come from a single observing station and are based on a necessarily inefficient detection system that senses only the high-energy tail of a neutrino distribution for one relatively insensitive step in a hypothesized chain of nuclear processes. The recently proposed neutrino mass can affect the predictions substantially.

(vii) Stellar Observation Facility Insights into solar variability can be achieved by the utilization of existing facilities such as the 60-inch Mt. Wilson telescope to monitor short- and long-period variations in other stars of solar type (Recommendations I.1.a and I.1.b). Parameters of interest are continuing brightness and spectral-line variations on time scale of days to tens of years.

(b) Suborbital Observations

Rockets continue to perform an extremely useful function as they have over the past decade as vehicles for powerful high-spatial-resolution ultraviolet spectrographs and ultraviolet coronagraphs (Recommendation I.1.b). They are also commonly in use as vehicles to carry radiometers for measurement of the solar constant and spectral irradiance (Recommendation I.1.a). Continued support is needed for rocket programs to develop new spaceborne instrumentation (Recommendation II.5) and also as a cost-effective vehicle for observations that do not require continuous coverage.

(c) Spaceborne Observations

(i) Solar Constant and Spectral Irradiance Instruments A dedicated and highly visible program of support is needed to bring to reality the oft-cited goals of long-term solar constant and solar spectral irradiance measurements (Recommendation I.1.a). An immediate development program is needed to bring about major improvements in solar radiometer design, stability, and laboratory standards. A carefully planned 22-year program to make use of opportunities on the Space Shuttle and other missions needs to be formulated and implemented with assurances of continuity. Crucial to its success and viability is the involvement of practicing scientists from the solar-physics community. In the spectral irradiance program, particular emphasis should be placed on defining the nature of photon flux variability in the 1500-3000 Å region, where solar fluctuations are of particular importance to the chemistry of the upper atmosphere.

(ii) *Solar Optical Telescope (SOT)* The SOT will provide images with 0.1 sec of arc spatial resolution of surface features of the sun to an interchangeable array of instruments, including a filter magnetograph and high-dispersion optical and ultraviolet spectrographs (Recommendation I.1.b). SOT missions are contemplated to last about a week. To take full advantage of the flexibility of this unique facility, there should be regular re-flights, as originally planned.

(d) *Theoretical Studies*

A balanced program to study the basic mechanisms of solar variability will require theoretical investigations including the following topics:

1. The investigation of physical mechanisms leading to possible variations in solar luminosity (S) on levels and time scales of climatological significance, i.e., $\Delta S/S \sim 10^{-3}$, $t \geq 1$ year (Recommendation I.1.a). Modeling of the solar convection zone to determine better the possible connection between such parameters as the solar diameter and the photospheric heat flux, and influences of variable magnetic fields on the total luminosity.

2. The continued study of physical processes leading to the intensification of strong magnetic fields, their emergence at the photosphere, and their dispersal and ohmic dissipation (Recommendation I.1.b). Such a study will require modeling of solar convection, with efforts to incorporate compressibility and magnetic Lorentz forces. The effects of the convection-zone kinematics, derived from these models, on magnetic fields in the solar interior require study in the context of dynamo theory and other concepts such as torsional oscillations. The general topic of magnetic-field behavior in a turbulent fluid must be investigated to learn more about the transport, stability, and dispersal of the fields over the range of spatial wave numbers observed at the photosphere. The decay of magnetic fields of opposite polarity in such turbulent velocity fields is still poorly understood. How does reconnection proceed? What role does the consequent ohmic dissipation play in the heating of photospheric, chromospheric, and coronal structures?

3. The further study of the dynamics of the corona, particularly in order to understand the relative roles of energy and momentum deposition in the acceleration process of the solar wind (Recommendations I.1.b and I.2.a).

4. The study of waves in the solar interior, in order to determine their role in transporting energy and angular momentum, and in the possible mixing of the nuclear burning core with outer regions of the solar interior. This would include continued close analysis of the acoustic p -modes as a useful diagnostic of convection zone conditions (Recommendation I.1.a).

5. The continued detailed study of conditions that produce flares, possibly leading to eventual ability to predict them. A close study of flare

precursors, such as changes in velocity patterns, oscillation modes, or magnetic structure, will be required. More refined modeling of the basic flare process will be required to understand the acceleration of high-energy particles and the nature of the continued heating in the decay phase. The magnetic stability of loop configurations must be investigated in more detail to study the likely role of instabilities causing the flare eruption.

(e) Data from Other Fields

Almost all of our hard knowledge of long-term solar behavior, including the existence of periods of anomalous behavior such as the Maunder Minimum, has come from proxy indicators such as tree-ring radiocarbon dating. Other, longer-lived isotopic tracers of solar activity such as beryllium-10 studies of sea cores and ice samples promise to extend our knowledge of solar variability as much as a million years or more into the past. The natural samples that are the basis for these studies and the methods of analyzing them (such as the conventional radioactive decay measurements of radiocarbon or new nuclear accelerator techniques) are in fields of science that are not traditionally funded through solar- or atmospheric-science agency offices. Tree-ring laboratories and radiocarbon analysis facilities are traditionally underfunded and short staffed. As solar studies come to depend increasingly on these data sources, provision should be made to provide STR support for such studies and for the facilities that are used.

2. The Interplanetary Medium

The particular aspects of research in the interplanetary medium emphasized below are linked with the achievement of the scientific recommendations presented in Chapter 2. The discussion of existing modes of ground-based observations below is not intended to suggest that the development of new ideas or techniques should be excluded. High priority should be given, for example, to the coordination of observations of optical/x-ray flares, radio bursts, coronal transients, and interplanetary scintillations (IPS) resulting from mass ejections and shocks. We give only a short discussion of some spacecraft missions, because a detailed and thorough discussion of them is available in a recent report of the Space Science Board, *Solar-System Space Physics in the 1980's: A Research Strategy*. (The major recommendations of that study are reproduced in Appendix A and in the NASA design study for the mission "Origins of Plasmas in the Earth's Neighborhood.")

In the following, we discuss those diagnostic observations obtained with ground-based and space techniques that we believe to be the minimum needed for both theoretical and modeling studies that fulfill the intent of the science recommendations in this area.

(a) *Ground-Based Observations*

(i) *He II Observations* He II 10830-Å observations (like those currently carried out at Kitt Peak, for example) should be continued (Recommendation I.2.a). These images of the solar disk provide a monitor of suspected coronal holes that appear at the solar east limb and then march, often with changed geometry, toward the central meridian. These solar image observations can be correlated with solar-wind-stream interactions detected by *in situ* techniques and help to define boundary conditions for solar-wind flow near the sun. They thereby reveal certain features of the heliosphere's structure and are already used as an early predictor of sustained activity.

(ii) *Radio Spectrographs and Interferometers* Radio spectrographs and interferometers (like those at Fort Davis and Clark Lake and the DOD SOON/RSTN* sites, for example) are needed to provide information for distinguishing the various processes (energetic particle streams, shocks, or trapped particles) that give rise to radio emissions. These observations are essential for implementation of Recommendation I.2.b on solar disturbances and the interplanetary "transmission line" because initial solar transient conditions (Type III electrons, Type II shocks) can be determined in this way. These observations also provide data on the three-dimensional structure of the heliosphere (Recommendation I.2.a).

(iii) *Neutron Monitors* A minimal network of neutron monitor stations necessary for implementing three-dimensional studies of cosmic-rays with energies > 1 GeV should have cones of acceptance as follows: (1) perpendicular to the ecliptic and at locations for which the threshold imposed by atmospheric and geomagnetic cutoffs are 2 GeV and 15 GeV, respectively, and (2) a high-altitude station at a location where the threshold is atmospheric rather than geomagnetic. The neutron monitor data address the basic nature of the heliosphere (Recommendation I.2.a). To achieve the goals of studying heliospheric anisotropies that arise from various transient phenomena and their energy dependence (Recommendation I.2.b), it is essential that the existing group of strategically located sites (maintained by the United States) be continued.

(iv) *Interplanetary and Spacecraft Scintillations* Scintillations of radio waves from small-diameter radio sources provide important information on solar-wind velocity and turbulence throughout the heliosphere on a regular basis (Recommendations I.2.a and I.2.b). Spacecraft telemetry signals can

*SOON and RSTN are abbreviations for the Solar Optical Operation Network and the Radio Solar Telescope Network, respectively.

also be used occasionally¹ to probe the lower corona. Studies of this type (those conducted by the Jet Propulsion Laboratory and University of California at San Diego, for example) should be continued and strengthened. These observations, preferably coordinated with those at the IPS facilities in Japan and India through the international program (STIP, Study of Travelling Interplanetary Phenomena) of the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) would provide valuable information from as yet inaccessible regions close to the sun, following the recommendations on the basic and disturbed interplanetary medium. During transient solar activity, Recommendation I.2.b would be served especially when coordinated with items (ii) and (iii) above.

(b) Suborbital Observations

We do not consider that observations in this category can, at the present state of the art, be given a high priority for studies of the interplanetary medium. However, as in the other specific disciplines, rockets may provide a means of testing innovations in instrumentation.

(c) Spaceborne Observations

As noted in our introduction, specific new spacecraft plans for the next decade have been considered in detail in previous studies, and we fully support those recommendations. Hence we consider here only recommendations for continued observations and the use of data from currently operating spacecraft. We also make some recommendations for instrumentation and future mission planning.

(i) Continued Observations The present network of deep-space probes, near-earth monitors, and ground-based observations should be exploited as fully as possible by coordinating multiple spacecraft observations of both normal conditions (Recommendation I.2.a) and nonroutine special events (Recommendation I.2.b) and by establishing mechanisms for rapid response. Examples follow:

- Continued tracking and extended mission for Pioneers 10 and 11 and Voyagers 1 and 2 will enable us to explore for the first time the outer regions of the solar system and will permit the study of the evolution of the heliosphere over one or more complete 22-year solar cycles.
- Simultaneous observations using imaging EUV, XUV, and x-ray photometers and white-light/Lyman-alpha coronagraphs would relate the solar and terrestrial ends of the sun-earth system. Missions that incorporate these techniques (such as Solar Maximum Mission, P78-1, System '90, and Pin-Hole Camera) should be encouraged.

(ii) *Long-Term Coordinated Observations at 1 AU* Plans should be developed for missions near 1 AU at superior conjunction permitting continuous and *in situ* solar-wind observations with plasma, magnetic field, energetic particle, and kilometric wavelength observations of high-speed streams and shocks from coronal holes and flares (Recommendations I.2.a and I.2.b). In the latter case, imaging devices on spacecraft that could view the side of the sun not visible from the earth would improve the reliability of predictions. It is especially important that adequate funds for the analysis of spacecraft observations from multiple locations be provided on a long-term dedicated basis. Coordinated studies of this type, like those conducted during the August 1972 flares and more recently (in 1977) by Helios-1 and -2, IMP-7 and -8, ISEE, and Voyagers 1 and 2, provide synoptic material essential for an understanding of the sun-earth linkage.

It is also important to continue long-term *in situ* solar-wind observations at 1 AU in the vicinity of the earth. The ISEE-3 payload made a start, which should be continued by the Interplanetary Laboratory (IPL) of the Origin of Plasmas in the Earth's Neighborhood (OPEN) mission and payload capabilities further developed for the future.

(iii) *Interplanetary-Magnetosphere Coupling Studies* It is of particular importance that we understand the coupling of interplanetary disturbances to magnetospheric processes (Recommendation 1.2.c.). For example, two schools of thought are prevalent at this time. In one, it appears that solar-wind energy can be stored within the magnetosphere and explosively released by the impact of a solar-wind disturbance (the arrival of a shock wave, or reconnection of the field lines at the magnetopause). In the other, it appears that a fraction (of the order of 1 percent) of the energy in the solar wind incident on the magnetosphere can be transferred to the magnetosphere with an efficiency that depends on the orientation of the interplanetary magnetic field carried by the solar wind.

A combined theoretical and observational program is needed. The latter should include dedicated monitoring of solar-wind plasma and magnetic fields of the type provided by ISEE-3, together with geophysical index monitoring of Dst (disturbance, storm) and AE (auroral electrojet). The former should include two-dimensional and three-dimensional magnetohydrodynamic computer modeling of solar-flare and coronal-hole disturbances and their propagation from the sun to the earth. The simulated results should be compared with observations upstream from and at the earth. Ideally, observations made near the sun and in the interplanetary medium would improve multipoint verification of our ideas about the sun-interplanetary-magnetosphere connection. The cause-and-effect chain should be checked with observations in the magnetosphere of the type to be provided by the OPEN mission, in order to examine the hypotheses of storage and release of energy.

(iv) *Heliospheric Boundary Probe* Planning should start for a probe to the heliospheric boundary (Recommendation I.2.a). Our horizon is at present being extended by Pioneers 10 and 11 and Voyagers 1 and 2. Because an understanding of the general structure of the heliosphere is essential to an understanding of STR, it is important that our exploration of critical regions of the heliosphere continue. They should be followed by a spacecraft with a sensitive, sophisticated instrumental complement to search for the heliopause, which, according to best current estimates, is possibly beyond 100 AU. Information on its existence, structure, and location will have an important bearing on solar-wind parameters, turbulence, and cosmic-ray modulation at the earth's orbit of interest to solar-terrestrial research.

(v) *Instrument Development* In order to use more fully the opportunities that future missions are expected to provide, we urge that the following areas of instrumental development be encouraged:

- Experimental systems for a solar probe mission (i.e., Star Probe), capable of withstanding thermal stress and offering large dynamical range.
- Solar-wind ion-mass spectrometers, providing better ion-mass resolution and faster time resolution. The study of the rarer ionic species would benefit substantially from the development of detector systems with larger collection rates.
- Innovative and coordinated instrumentation, developed to study the most significant aspects of turbulence and fluctuations in the interplanetary medium. Close collaboration between experimenters and theorists should be encouraged for defining experimental design and goals.
- Cosmic-ray detectors, able to measure particle charge states in the energy range from 1 to 10 MeV/charge. The development of large-area detectors to study particle composition, three-dimensional anisotropies, and fast time variations is also desirable.

(d) *Theoretical Studies*

Several processes in the interplanetary medium, the theoretical study of which would serve the goals of both Recommendation I.2.a (steady-state structure) and Recommendation I.2.b (transients), are noted below.

A comprehensive study of physical processes in the interplanetary medium must focus on some of the specific individual problems whose understanding is essential if the overall goals are to be realized. NASA's Solar Terrestrial Theory Program is making a good beginning on this.

(i) *Charged-Particle Propagation and Transport* We must understand how dynamical processes, including transients in the interplanetary medium, are affected and controlled by the three-dimensional structure of the heliosphere.

It is necessary that we develop a theory of charged-particle propagation in the interplanetary medium. This is an important aspect of implementing the recommendation on the steady-state heliosphere.

(ii) *Interplanetary Acceleration Processes* Theories of solar-wind particle acceleration by propagating shock waves or by planetary bow shocks are needed. As in the propagation theories mentioned above, the understanding of these acceleration processes also requires a knowledge of the nature of interplanetary fluctuations and of how particles propagate through such fluctuations. Although current efforts have demonstrated good agreement between numerical experiments and theory, these show serious discrepancies with observation. It must be that some important physical processes are missing from the numerical and theoretical models. Two approaches are currently being studied. The first is the stochastic acceleration of particles by shock waves and turbulent plasma ahead of or behind these shocks; the second is a gradient-B drift set up by the $\mathbf{V} \times \mathbf{B}$ field in the shock frame. Both of these approaches should be fully exploited, together with consideration of the global flow fields provided by modeling and observational studies.

(iii) *Turbulence and Fluctuations* To understand the observed nature of plasma and magnetic fluctuations, a vigorous effort involving analytical and numerical techniques is necessary to answer such fundamental questions as the following. If fluctuations are waves, then which wave modes predominate, and how do they evolve in the solar wind? If these fluctuations are "turbulence," then what is the statistical nature of this turbulence? Other aspects will require new missions, as noted above, in which experimenters and theorists collaborate closely on experimental design and goals.

(iv) *Magnetohydrodynamic Modeling* Related problems requiring continued, if not increased, attention include the development of magnetohydrodynamic time-dependent two- and three-dimensional multifluid codes, including "anomalous" transport coefficients. Self-consistent models, including higher-moment equations, are necessary to examine non-Maxwellian distribution functions, anisotropies, particle beams, heat flux, and thermal conductivities. It is essential that the theoretical computer modeling of shocks, various discontinuities, and Alfvén waves be compared with *in situ* observations and ground-based observations. These theoretical studies provide a codification of ideas and a formulation of unifying concepts. These studies should proceed on their own independent course instead of attempting to explain specific observations. Their results should be compared with observations from several sources when deemed appropriate by the independent theoretician.

3. Magnetosphere-Ionosphere

The accomplishment of the scientific recommendations presented in Chapter 2 requires that a specific research program be carried out in the magnetosphere and ionosphere. A quantitative understanding of the physical mechanisms governing particle and energy transport in the near-earth space environment requires a carefully planned program of spacecraft, rocket, balloon, and ground-based observations. *In situ* measurements with spacecraft in the solar wind, in high-inclination orbits, and in the distant magnetotail are essential to gain an overall view of magnetosphere energy-transfer processes. These measurements must be complemented at times with balloon observations, high-latitude rocket experiments, and appropriate ground-based measurements for the detailed study of small-scale structures.

An implementation strategy for space-based studies of solar-system plasmas in the 1980's has been developed by the Committee on Solar and Space Physics (CSSP) of the Space Science Board. The main recommendations of their study are reproduced in Appendix A. Their strategy has four major elements: a two-satellite atmospheric research effort [the Upper Atmosphere Research Satellites (UARS)], the four-satellite magnetosphere-interplanetary research effort (OPEN), a Shuttle-based program for solar physics that begins with the Solar Optical Telescope (SOT), and the Dynamics Explorer. This strategy is compatible with the science discussions in Chapter 5 and is central to future national efforts in solar-terrestrial research. Because these elements of the CSSP strategy are covered in depth in their report, they are only outlined briefly below in Subsection (c).

Our implementation strategy for ground-based and suborbital studies of solar-system plasma processes is based on the scientific discussions and resulting recommendations in Chapter 2. Ground-based and suborbital observations of the ionosphere and upper atmosphere at high geomagnetic latitudes will be of great importance in the next decade to furnish crucial information on magnetospheric processes. The advantage of passing relatively slowly through the various ionospheric projections of magnetospheric regions offers important opportunities for seeing temporal and spatial variations, which are often missed or are difficult to interpret from satellite observations.

(a) Ground-Based Observations

(i) *Integrated Station Arrays and Unmanned Stations* Developments in electronics and sensor technologies have provided, during the last decade, a greatly increased capability for "conventional" geophysical instrumentation such as magnetometers, riometers, and VLF receivers. Similar improvements have been made in data acquisition, transmission, and processing techniques.

Arrays of observatories with such instrumentation are now being used to provide near-real-time information on the state of magnetosphere-ionosphere interactions for general predictive purposes. They are also being used to permit the accurate assessment of complementary data sets (e.g., auroral radar, satelliteborne detectors), where information on important boundaries in the magnetosphere such as the polar cap, the equatorward border of the auroral oval, the plasmopause, and substorm-disturbed regions is a requirement (Recommendation I.3.a.).

The next decade should feature the continued development of more effective low-power data-acquisition and preprocessing systems for use in remote regions like Antarctica, where, up to now, it has been almost impossible to set up arrays with optimum station spacing. These arrays should involve remote unmanned observatories, possibly powered with energy extracted from the local environment. There will be a need to develop high-quality software for the storage and display of the various types of data that will be acquired.

Together with the advanced development of remote array capabilities should be the continued operation (either manned or unmanned or a combination thereof) of a high-resolution array to monitor continually the magnetospheric energy dissipated in the near-earth environment. A chain, like that in the Alaskan sector, could be connected for data acquisition to other key stations in the Scandinavian sector to achieve a transpolar configuration nearly along a magnetic meridian. Such a configuration is of fundamental importance to study, on a continuous basis, noon-midnight and dawn-dusk asymmetries of the entire polar cap and the auroral oval current system.

(ii) *Coherent-Scatter Radar* The coherent-scatter radar technique is based on the measurement of the Doppler shift of VHF radio waves scattered from moving plasma irregularities associated with ionospheric currents. Through the use of range-gating techniques and two multiple-beam receiving antennas, a closely packed set of drift velocity measurements (about 400 points distributed over an ionospheric area of about 230,000 km²) can be obtained from those regions where ionospheric currents are present with sufficient intensity to establish the irregularities required to scatter the VHF signal (Recommendation I.3.b).

In order to obtain appreciable coherent scattering, the probing radio waves must be directed nearly perpendicular to the local magnetic field at the ionospheric height where the irregularities produce the scattering. This condition becomes increasingly difficult to satisfy as one progresses toward the magnetic pole. There is an observational threshold set by the relative velocity between electrons and ions: when the ionospheric electric field is less than about 15 mV/m, there are too few irregularities to yield an identifiable return signal.

Results from the currently operating STARE radar system in Scandinavia have provided important new views of the distribution of the electric field near the aurora, as well as the temporal variations of the electric field associated with hydromagnetic waves. In conjunction with satellite magnetometer data, it has been possible to obtain some new results on the latitudinal distribution of magnetic-field-aligned currents. The economy of this technique should foster its deployment at several locations in the auroral zone, extending in longitude to yield an instantaneous view of plasma convection and the quasi-dc and transient electric fields.

(iii) *Incoherent-Scatter Radar* The incoherent-scatter (IS) radar technique provides the local plasma density. Ion-drift speed and the temperatures are derived from the frequency displacement and spectral shape of the received signal. Pulsed IS radar provides range discrimination with simultaneous multiple measurements of the received signals at designated altitudes. Using the altitude profiles of the derived densities, temperatures, and drift velocities, one can deduce additional information about ionospheric electric fields, E-region current densities, ionospheric conductivities, Joule heating rates, ion-neutral collision rates, E-region neutral winds, energetic particle precipitation characteristics, and ion recombination rates (Recommendations I.3.a and I.3.b).

For radar like that at Chatanika, Alaska, observations become difficult when the electron density is less than about 10^4 cm^{-3} . For a monostatic radar, the ion-drift velocity vectors are obtained from spatial and temporal averages. Multiple receivers, such as those to be deployed around the European incoherent-scatter (EISCAT) facility, can substantially improve the spatial resolution of the velocity measurements.

Currently existing IS radars include those at Chatanika (Alaska), Millstone Hill (Massachusetts), Arecibo (Puerto Rico), Jicamarca (Peru), St. Santin (France), and in northern Scandinavia. The establishment of an IS radar at a very high geomagnetic latitude site is the foundation of our national plan for ground-based studies of the polar cusp, the polar cap, and the high-latitude edge of the nightside auroral oval (Recommendation I.3.a).

(iv) *Optical Measurements* Three distinct categories of optical measurements have provided a wealth of unique observations of the magnetospheric, ionospheric, and atmospheric environment. First, optical imaging on the "ionospheric TV screen" provides information on magnetospheric processes revealed in the form of auroras (Recommendation I.3.a). Second, spectroscopic investigations provide a quantitative tool for studying the complex chemistry of ion and neutral species in the high atmosphere, particularly as related to metastable species and minor constituents (Recommendations

I.3.a and I.3.b). Third, interferometric measurements of selected emission lines are a relatively low-cost means for obtaining systematic data of ion motions and neutral winds, important parameters for studying global thermospheric circulation and magnetospheric convection (Recommendation I.3.b).

Optical measurements of natural atomic or molecular emissions can be very cost-effective and should therefore take advantage of recent developments in detector technology. Innovation in some fundamental optical concepts and radical changes in capabilities make possible new instrumentation. The widely used photographic all-sky camera, imaging with light from the total auroral spectrum, weighted according to the response of the film used, should be replaced with electronic monochromatic imagers (e.g., image tube or charged-coupled diode arrays). Such electronic imagers, providing both spatial and spectral information, would replace not only the all-sky camera but also the conventional meridian-scanning photometers. High-spectral-resolution systems are needed for the observation of the daytime auroras at those northern hemisphere sites where adverse solar illumination is encountered. Multiple-*étalon* Fabry-Perot interferometers would allow optical observations of dayside auroras. High-throughput spectrophotometric facilities are required to monitor the low level of optical emissions from the metastable atmospheric species. Optical Doppler techniques are now being used to measure atmospheric winds from the ground and will in due course be made from space.

(b) *Suborbital Observations*

(i) *Balloons* Instruments flown on zero-pressure balloons have provided information on such variables as electron bremsstrahlung x-ray fluxes and ionospheric electric fields, all of which are important for studying a number of magnetosphere-ionosphere processes. In the future, zero-pressure balloon platforms will continue to be an effective means of obtaining data at stratospheric heights in support of active experiments and in conjunction with concentrated campaigns for the study of specific phenomena. A major new development in ballooning technology involves superpressure balloons that have been used recently in the southern hemisphere for long-duration flights concerned with middle-atmosphere objectives. At present, there is no well-defined routine for easily obtaining launch support for superpressure balloon payloads. Balloon launch opportunities should be treated like satellite opportunities, and scientific teams should be chosen from individually submitted proposals for specific mission objectives.

(ii) *Sounding Rockets* Sounding rockets are the only vehicles able to transport scientific instrumentation for *in situ* measurements in the 40- to 120-km-altitude region: they are also the only "slow-moving" observation platforms

available at satellite altitudes. Rocket launches can be timed for specific geophysical (auroral) situations and often afford temporal and spatial resolution unattainable with satellites. The use of rocket platforms provides opportunities for graduate students to conduct original research for advanced degrees, opportunities that essentially no longer exist with the long lead times that satellite experiments require. In the last decade, several fixed sounding-rocket launching sites have been closed or reduced in operations. Further reductions would virtually eliminate this valuable capability.

In the future, sounding-rocket platforms will be used principally for the detailed multiparameter and multipoint study of specific magnetosphere-ionosphere problems and for active experiments. "Cause-and-effect" experiments that use rocket platforms for both the active portions of the experiment and for diagnostic instrumentation will likely become important facets of suborbital research technology in the 1980's. Some investigations of natural phenomena will require active releases from rockets as well as comprehensive ground-based diagnostics.

There is a clear need for rocket platforms capable of probing the important auroral acceleration zone above about 3000-km altitude from appropriately located launch sites. Multirocket launches for electric-field measurements at lower altitudes below the acceleration region will also be necessary.

(iii) Active Experiments The behavior of the magnetosphere-ionosphere system is governed by physical mechanisms that are part of extremely complex chains of cause-and-effect relationships. The dynamics of these strong feedback systems are difficult to understand quantitatively solely on the basis of observations of natural perturbations that are highly unpredictable and whose initial conditions are often difficult to establish.

There are basically four types of possible man-made perturbations: (1) injection of electromagnetic waves of appropriate frequency, intensity, direction, and time envelope; (2) injection of charged-particle beams of given energy, intensity, and direction; (3) injection of plasma clouds or beams of given composition, temperature, and bulk speed; (4) injection of neutral chemicals.

Some of these controlled experiments are of the type called "tracer experiments" or "active probing," in which the injected signal does not carry enough power or energy to cause a measurable perturbation of the medium. In such experiments it is the propagation or evolution of the signal itself that is used as the active probe to observe the prevailing natural conditions. We are pleased to note that NASA is undertaking a significant program of active experiments using three of the above four types of perturbations. Transmitters and accelerators on Spacelab are under development for experiments (1) and (2) above. A joint U.S.-German effort, Active Magnetosphere Particle Tracer

Explorer (AMPTE), will trace the entry of tracer chemicals from the solar wind into the magnetosphere. On the other hand, some man-made perturbations are "nondeliberate," such as electromagnetic radiation emitted by electric power networks and radio communication antennas and chemical releases into the upper atmosphere as products of high-flying aircraft or rocket motor combustion, and may cause significant overall changes.

Ground-based VLF wave-injection experiments have proven most valuable to study the interaction of waves and energetic particles in the magnetosphere and in energetic particle precipitation. Radio-frequency heating experiments operated in the continuous wave (cw) mode have been used to study the role of parametric instabilities in the ionosphere. Shaped-charge barium injections from sounding rockets have been successfully used to determine the electric field in the vicinity of auroral arcs and to study the relationship between striations and ionospheric instabilities. Electron-beam injections from rockets have been used to measure the bounce and drift motions of particles on magnetic field lines near the trapping boundary, to study beam-plasma instabilities in space, and to induce local instabilities and waves. Chemicals released into the upper atmosphere and the ionosphere are used to measure wind profiles at high altitudes and have been used to modify the ionospheric conductivity under controlled conditions. Finally, active experiments have provided, and continue to provide, valuable information on some of the local effects expected to occur during high-altitude nuclear detonations.

The chemical release module, the electron accelerator, and the wave-injection facility, all proposed for Space Shuttle flights, are examples of major facility-class active experiment developments proposed for the future. Major rf heating transmitters operating in a cw mode are being built at mid-latitudes near the Arecibo IS facility and in the auroral zone near the European IS facility. There is laboratory evidence that experiments using high-power-density, pulsed-plasma-wave excitation can lead to caviton formation, particle energization, and nonlinear interactions in the high-latitude ionosphere. Operated in a double-frequency mode with beat frequency in the VLF range, such high-power pulsed beams could be used to excite ion-acoustic, ion-cyclotron, whistler, and lower hybrid waves. Further study should be made of the possible results and implications from such high-peak-pulse injection experiments conducted near an IS radar and rocket launch facility.

Ion injections in the distant magnetosphere will provide an important tool to study particle transfer mechanisms through boundary layers and associated acceleration mechanisms. Multiple, or multirocket, shaped-charge ion injections conducted simultaneously at different points in the neighborhood of an auroral arc should be carried out to provide information on the fundamental issue of the nature of parallel electric fields responsible for auroral particle acceleration above auroral arcs.

(c) *Spaceborne Observations*

The implementation of solar-terrestrial research in the 1980's using spaceborne instrumentation was developed in depth in the report by the Committee on Solar and Space Physics, *Solar-System Space Physics in the 1980's: A Research Strategy*. The scientific basis for this strategy was largely laid in the Space Science Board report *Space Plasma Physics: The Study of Solar-System Plasmas*. The major recommendations of both of these studies are quoted in Appendix A and may be summarized as follows:

(i) *Origin of Plasma in Earth's Neighborhood (OPEN)* The OPEN program as currently conceived consists of spacecraft at four locations [upstream interplanetary space, the distant ($>200 R_e$) geomagnetic tail, the near-equatorial magnetosphere, and high above the earth's north polar cap]. A comprehensive instrument complement will make simultaneous measurements at each location in order to ascertain the flow of energy and momentum from the interplanetary medium, through the earth's system and ultimately energy deposition on top of the upper atmosphere.

(ii) *The Solar Optical Telescope (SOT)* The SOT is a Shuttle-based instrument with 0.1 sec of arc spatial resolution to study surface features of the sun, using a variety of focal-plane instruments.

(iii) *Upper-Atmosphere Research Satellite (UARS)* In addition to OPEN and SOT, the UARS spacecraft will complement the ionosphere-atmosphere element of these measurements. These programs will follow the Dynamics Explorer spacecraft, which will study magnetosphere-ionosphere coupling by means of comparisons of simultaneous high- and low-latitude measurements, comprising particle distributions, field-aligned currents, and electric and magnetic fields.

These four NASA programs form the core of a national effort in solar-terrestrial research and understanding in the next decade. We fully support these programs, and the magnetosphere-ionosphere implementation plan that we present in this chapter complements these spaceborne observing programs.

(d) *Theoretical Studies*

The data-gathering phase of the International Magnetospheric Study (IMS) was conducted in the four-year period 1976-1979. Coordinated ground-based, atmospheric, and space observations took place during the IMS on an unprecedented scale. Large amounts of scientific data have been accumulated from space missions, both IMS-related and nonrelated. In part, this is a result of the fact that most satellites continue to function long after their designated prime

mission phases. Data handling and management have become a problem because of the staggering amounts of data produced and the ever-increasing needs to conduct multiparameter studies.

The period 1980-1985 has been designated as the Post-IMS Data Analysis Phase, whose objective is to promote analysis and theory in an organized, coordinated way. A major accomplishment of the IMS has been the quick availability at the World Data Center A for Solar-Terrestrial Physics, NOAA (Boulder, Colorado) of data obtained from an extensive array of ground-based magnetometers and distributed in near real-time by the NOAA Environment Laboratory Data Acquisition and Display System. This successful experience in data handling and management should provide a basis for the development of data systems for solar-terrestrial research in the next decade.

Theory and computer modeling must play a more integral role in the future development of solar-system physics. In addition to basic theoretical studies of an analytical nature, important contributions to the development of magnetospheric physics will come through computer modeling and simulation efforts. Quite recently, NASA has implemented significant new endeavors in the support of solar-terrestrial theory as a result of the Space Science Board study, *Space Plasma Physics: The Study of Solar-System Plasmas*.

(e) *Summary and Priorities*

In terms of *ground-based measurements*, the principal priority in the first portion of the decade should be placed on the development of new ground-based instrumentation and data-handling techniques for use in studies of high geomagnetic latitude phenomena and for studies of magnetosphere-ionosphere coupling. *Of equal priority* during this time interval should be the analysis and theoretical interpretation of the extensive suites of data acquired during the IMS.

The above two priorities for ground-based research can probably be accomplished only with a significant decrease in some existing conventional ground-based observational work. With the exception of the operational portion of one or two key U.S. chains, such as the multi-instrumented array in the Alaskan sector, the resources thus freed should be devoted to the interpretation of IMS data and to instrumentation development, including sensors and data handling. The selection of the research efforts in these two areas should be through the standard peer-review process.

Later in the decade, new ground-based observations, carried out both in isolation and in coordination with the UARS and OPEN spacecraft, will be required to implement the scientific objective for the study of geophysical processes at very high geomagnetic latitudes. Many of the studies of these processes can be attacked well using the incoherent-scatter radar techniques at these latitudes. The full benefit of such a facility can only be achieved by

the ready availability of data from suitably spaced arrays (unmanned or manned) of ground-based instruments both in the vicinity of a radar and at other appropriate locations. Such arrays and observational complexes should contain modern optical, magnetic, and radio-wave instruments and data-handling systems.

Studies of the scientific objectives involving magnetosphere-ionosphere-atmosphere coupling will require the acquisition of data at auroral and subauroral locations, both in cooperation with, and independent of, a very-high-latitude radar facility and closely associated arrays. The appropriate instrumentation for these coupling studies will depend on the physical processes being studied and the inventiveness of the individual investigators. The coherent-scatter radar technique will most likely play important roles in this research.

The advent of the Space Shuttle, even a polar-orbiting Shuttle, will not negate the usefulness of balloons and rockets as platforms for studying a number of problems in space plasma physics. Investigations of the structure of auroral arcs and studies of the high-altitude auroral acceleration regions will require rocket capabilities. Balloons will continue to be of importance as platforms for studies of electron-produced x rays and of atmospheric and ionospheric electric fields. The appropriate development of the capability for long-duration balloon flights may, in the future, become important for studies of high-latitude magnetospheric phenomena.

Active experiments will play an increasing role in some aspects of magnetospheric physics, particularly those problems that elucidate specific mechanisms in the geospace environment. Rockets will continue to be required for carrying gas releases into various regions of the geospace environment to measure winds, electric fields, and other parameters and to trace magnetic field lines and elucidate physical processes operating along them. Wave-injection experiments will continue to explore the reasons for particle loss from the magnetosphere and provide crucial insights into magnetosphere-atmosphere coupling processes.

4. The Atmosphere

In order to achieve the scientific goals presented in Chapter 2 it is necessary to carry out certain programs of research in the middle atmosphere and in the thermosphere. The research needs outlined below reflect the judgments of the present study and are consistent with the previous CSTR study on the upper atmosphere, *Upper Atmosphere Research in the 1980's: Ground-Based, Airborne and Rocket Techniques*. The principal recommendations of this earlier study are quoted in Appendix A. The fact that the plan described below is

intended to achieve the scientific objectives of the recommendations in Chapter 2 does not imply, however, that new techniques and/or scientific needs not anticipated here should not also receive careful consideration. Finally, the requirements discussed in this section appear to be consistent with current agency funding projections and so do not anticipate the need for any significant increase in funding.

The level of our present-day understanding of the chemical and physical behavior of the thermosphere is different from that of the middle atmosphere, primarily because the two regions have not been equally accessible to measurements. The thermosphere has been probed by satellites, rockets, ground-based radar, and optical techniques for a number of years. By contrast, the middle atmosphere has been probed infrequently, chiefly by balloons and rockets and only recently (using remote-sensing techniques) from satellites. Therefore, the requirements for implementing the major scientific objectives are different for the thermosphere and middle atmosphere. We emphasize the importance of recent discoveries in the middle atmosphere, as related to effects of human input, and recognize that the momentum now established in studying this region of the atmosphere must not be lost. The problem associated with the fragility of the ozone layer, to name one conspicuous recent problem, illustrates the importance of understanding all regions of the atmosphere surrounding us.

These considerations have led to the initiation of the Middle Atmosphere Program (MAP), an international program of intensive study of the middle atmosphere that has been designed for the time period 1982-1985. The current position regarding the U.S. contribution to MAP has been described in a recent CSTR report, *The Middle Atmosphere Program: Prospects for U.S. Participation*.

(a) *Ground-Based Observations*

(i) *Very-High-Latitude Radar* An incoherent-scatter radar at very high latitude needs to be established in order to observe the energy and momentum input into the atmosphere from the cusp and dynamic processes in the polar cap. Consideration should be given to a site that aligns the existing western hemisphere radar stations in a meridional chain to study global dynamics effectively. Since energy propagation from the high-latitude auroral region is equatorward, the meridional chain is important for studying the equatorward propagation of electric fields and ionospheric perturbations as well as neutral wind, temperature, and composition responses. The appropriate upgrading of the existing subauroral latitude radar is an important part of this plan (Recommendation I.3.b).

(ii) *Atmospheric (MST and ST) Radars* Radars can detect echoes created by turbulence in the neutral atmosphere as a means of studying atmospheric motions. The mesosphere-stratosphere-troposphere (MST) and stratosphere-troposphere (ST) radar capabilities should be exploited to gain a better understanding of the importance of small-scale motions in the overall dynamics of the middle atmosphere. Studies should also be undertaken to examine the potential scientific return of a more extensive network of MST and ST radars (Recommendation I.4.a).

(iii) *Spectroscopic Methods* It is now possible to study all regions of the middle atmosphere and thermosphere from the ground by methods that apply wavelength discrimination. Absorption and emission spectroscopic studies, at a wide range of wavelengths, from the optical to the radio, provide a powerful tool to identify particular atmospheric species unambiguously. Observations of the shift and shape of the spectral lines at very high resolution lead to information on atmospheric temperatures and winds. Active lidar techniques are now well established as being capable of measuring temperatures, winds, and certain minor atmospheric species in the middle atmosphere. The recent rapid advances in detector and data-handling technology should lead to significant improvements in these observations, which need to be continued and expanded during the next decade. Meaningful coordination among the groups carrying out these observations should be encouraged in order to help in elucidating the large-scale dynamics and chemistry in the middle atmosphere and thermosphere (Recommendation I.4.b).

(iv) *Auroral Facilities* Magnetometer, auroral imaging, and optical spectroscopic data are useful for estimating magnetospheric energy input into the atmosphere and its spatial and temporal variations. Since these methods are the only way to obtain information on global energy inputs, a means for collecting and disseminating data on high-latitude magnetic disturbances and auroral images should be maintained (Recommendations I.3.b and I.4.a).

(b) *Suborbital Observations*

A vigorous program of *in situ* and remote-sensing observations from aircraft, balloons, and rockets needs to be pursued to investigate the chemistry, dynamics, and electrical properties of the middle atmosphere. Direct sampling of the middle atmosphere is an especially difficult undertaking, and, therefore, the development of new and/or novel concepts needs to be encouraged. Direct measurements are important for investigating detailed chemical-reaction processes. Thus, even with a strong program of satellite and ground-based remote sensing, it is essential that the capability for *in situ* measurements

from aircraft, balloons, and rockets be preserved. The sounding-rocket program has been cut and threatened on numerous occasions in recent years. It is imperative for the health of atmospheric research that a viable national sounding-rocket program be maintained during the 1980's (Recommendation I.4.a).

(c) Spaceborne Observations

(i) Upper-Atmosphere Research Satellite (UARS) A proposed satellite program (UARS) has been described in detail by an earlier planning group. This is a multisatellite program that will be able to investigate the radiative energy balance, chemistry, and dynamics of the stratosphere, mesosphere, and lower thermosphere. This program is the backbone of our national plan to study the basic state of the middle atmosphere, its natural variability, and response to various solar-terrestrial perturbations. The U.S. contribution to the Middle Atmosphere Program (MAP), a major international program that was established to study the energetics, dynamics, and chemistry of the middle atmosphere was, to a large degree, tailored and timed to take place around the first two UARS launches. It is important from both a national and international point of view that this satellite program be carried out soon (Recommendation I.4.a).

(ii) Spaceflight Opportunities In the 1980's there is a need to develop atmospheric measurement capabilities for both Space Shuttle and free-flyer spaceflight opportunities. For short-duration Shuttle missions, support is necessary for the development and flight of new facility-class instruments that will effectively probe the atmosphere with high spatial, temporal, and wavelength resolution. The continued development of instruments, using the latest technology, must be an integral part of such a program. Moreover, as pointed out by the CSSP report, "it is essential that Shuttle-class instruments be kept in space longer than one week at a time." This is necessary for studying atmospheric processes having longer time scales than Shuttle flight times and also for investigating intermittent solar-terrestrial perturbations. Shuttle instruments currently being developed might eventually be combined with a power source (such as the proposed 25-kW Power Module) to create a free-flying Solar-Terrestrial Observatory.

(iii) A Satellite for Investigating Global Thermospheric Dynamics Consideration and planning for a satellite in a high-inclination orbit that incorporates the latest instrumental techniques should begin in the late 1980's. This satellite is needed to investigate thermospheric dynamics from F-region heights down to the mesosphere and should be able to probe composition,

winds, and temperatures in the lower thermosphere and mesosphere and atmospheric response to auroral activity. It will complement the meridional chain of incoherent-scatter radar facilities, spanning the region from the polar cusp to the equator discussed above. Together they will provide a unique opportunity for a systematic exploration of the global response of the thermosphere and mesosphere to auroral inputs, solar ultraviolet changes, and lower atmospheric perturbations, such as planetary waves and tides, as well as determining the nature of any instabilities in the general circulation. The satellite and radar measurements should be coordinated and supplemented by measurements from the network of ground-based optical observatories with a capability of measuring winds and temperatures in various thermospheric airglow emission regions (Recommendations I.3.b and I.4.a).

(d) Theoretical Studies

There is a need for the continued development of general circulation models for both the thermosphere and middle atmosphere to incorporate the findings of the experiments identified in the recommendations and to guide further the optical and experimental effort. Since these models generally incorporate only parameterized chemical schemes for computational efficiency, there is also a need for continued development of one- and two-dimensional chemical transport-radiative balance codes.

Part II

5

The Solar-Terrestrial System

I. INTRODUCTION

It is obvious that the sun affects the earth, but until quite recently most scientists believed that the only important effect was the bathing of the earth with a uniform, constant flux of electromagnetic radiation, mostly visible light and infrared heat, with a little ultraviolet radiation added. Indeed, this flux is called the "solar constant." Over the past few decades, and especially since the beginning of the Space Age, this view has changed. We have become aware of the existence of a vast, interrelated system in which many forms of energy propagate and matter travels from the sun to the earth, and on beyond to the most distant planets. The study of the various parts of this system, with their couplings and interactions, has become known as solar-terrestrial research* (or solar-planetary research, if planets other than the earth are explicitly emphasized). The component parts of the *system—the sun, the interplanetary medium, and the magnetospheres, ionospheres, and atmospheres of the earth and other planets*—are described in more detail below. We shall call

*Usage is not yet quite uniform. The term "solar-terrestrial physics" has the widest international currency, and the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) of the International Council of Scientific Unions is so designated. But atmospheric chemistry is certainly involved in solar-terrestrial processes, and even biology, in that the vegetative ground cover affects atmospheric chemistry; thus many prefer a term with a wider connotation than "physics." Other terms enjoying wide currency are "solar-terrestrial relations" or "relationships." In all these, "planetary" is substituted for "terrestrial" when the broader context is appropriate. For example, the American Geophysical Union uses the term "solar-planetary relationships" for its Section in this field of interest.

particular attention to the close interrelationships and feedback between the various parts of the system.

II. THE SUN

1. Introduction

The sun is a glowing ball of intensely hot gas held together by its own gravitational field. The mass of this gas is so large that the density and pressure, and hence temperature, are sufficient to initiate and maintain nuclear reactions. Fusion, or the nuclear combining of hydrogen atoms to create heavier elements, must be the ultimate source of the sun's enormous outpouring of energy from the photosphere, the deepest directly visible layer of the atmosphere. (The photosphere looks like the sun's surface, because the gases above it are transparent; but a gaseous ball has no well-defined surface.)

The energy derived from nuclear reactions does not all go directly into heat that is radiated into space. In the deepest solar interior, the energy liberated by the proton-proton, or p-p, chain first works its way outward toward the surface in the form of energetic or short-wavelength "hard" x rays, then as less-energetic "soft" x rays, and ultraviolet radiation. Eventually this radiation is absorbed in the outer layers, and the heated gas expands and rises. This outer region is known as the convection layer or zone and extends to a depth of roughly a quarter of the solar radius below the photosphere. The motions of the ionized gas, or plasma, in the convection zone twist and tangle the internally generated solar magnetic field that is embedded in the plasma, stretching the field lines like rubber bands and squeezing them closer together in places, thus creating intense local fields.

At any given time, a significant part of the energy generated near the sun's center may be diverted in the convection zone and stored there in coils of twisted magnetic fields, in the kinetic energy of convective gas motion, or in an increase of the sun's potential energy through expansion of the sun's diameter. In view of the complexity of our star's inner workings, it would be somewhat surprising if the amount of heat reaching the visible surface, and thus the sun's luminosity, were exactly constant. Thus an essential ingredient of a theory of solar-terrestrial research is a better observational understanding of how this output of light and heat might vary. What we believe to be important initiatives in this direction are discussed below.

The intensified magnetic fields generated in the convection zone tend to rise to the surface under the action of the sun's convective motions coupled with the remarkable property of their own buoyancy. The localized tubes of intense field appear at the photosphere as magnetic active regions of various

sizes, which are the scene of dark sunspots and also bright areas, called "plages."

There is increasing evidence that some of the energy stored in subsurface magnetic-field coils dissipates when it emerges at the photosphere and is converted into other forms of energy, thus increasing the local output of x-ray, ultraviolet, and radio-frequency (rf) emission by very large factors. Although the fraction of the sun's total radiated energy emitted at these wavelengths is very small (less than 1 part in 10^4), the resulting modulation is profoundly important for the chemistry of the earth's upper atmosphere. The most extreme cases of localized excess energy output are associated with catastrophic eruptions known as flares; the x-ray emission may then rise by a factor of 100 or more in a few minutes. Thus, a close study of changes in the distribution of solar energy in wavelength, or spectral irradiance particularly at these short wavelengths, is critically important to solar-terrestrial research.

The dissipation of magnetic fields at the photosphere, and above it in the chromospheric and coronal layers of the solar atmosphere, not only affects the sun's radiation and its spectral distribution but also the outflow of magnetized plasma into the interplanetary medium. At times, flares unleash in explosive outbursts the stored energy of the magnetic field accumulated slowly in the convection layer. Flare eruptions heat the solar atmosphere tremendously and also hurl large volumes of gas into the interplanetary medium toward the earth's orbit. The gas drags the embedded solar magnetic field lines with it.

The sun's magnetic fields also shape the general steady outflow of plasma. In the active regions, the field lines emerge from the interior and return locally, in arches that cover only a small fraction of the solar surface. Elsewhere, the gradual evolution of the magnetic field produces the so-called "coronal holes." In these, field lines are open and stretch beyond the earth's orbit, allowing magnetized plasma to be accelerated outward, eventually to stream past the earth at speeds ranging from 200 to 800 km/sec (or 0.5 million to 2 million miles per hour).

It has been discovered that the whole field pattern extending beyond the earth's orbit to at least as far out as Saturn changes its magnetic polarity every 22 years. This long-term process is still mysterious.

One ultimate goal of solar-terrestrial research is to understand and predict all the processes that connect observable changes on the sun to significant influences on our environment. To achieve this goal, we must observe the variable output of radiation and magnetized plasma from the sun in considerable detail. For the purpose of making predictions, we also need to understand the dominant physical mechanisms responsible for the modulations, from short to long time-scales. We describe below three selected areas of solar research that are central to solar-terrestrial research. These are the

variation of solar luminosity and spectral irradiance, the basic mechanisms of solar magnetic activity, and the variable solar output of magnetized plasma.

2. Variation of Solar Luminosity

The solar output of light and heat appears to vary, at least slightly, in total power and more significantly in its distribution with wavelength. Both types of variation have important consequences for the earth's upper atmosphere. Therefore, a first goal of any study of solar luminosity is to measure the variation of the solar constant over time scales from seconds to centuries. These are needed as inputs to climate models and eventually in climate prediction, if solar variation can be predicted. There is no question about the sensitivity of global temperature and climate to variations in the total solar flux. Present calculations indicate that a persistent change of 0.1 percent in the solar constant might well produce a significant change in climate.

A second purpose of solar-luminosity studies is to discover why the solar output varies. To do this, we need to understand the mechanisms for the generation, transport, and storage of solar energy in the solar interior. Existing measurements of the solar constant from ground level, from high-altitude platforms, and recently from spacecraft have established that the solar luminosity is constant to better than 1 percent over the roughly 50 years during which there has been a U.S. program of ground-based measurements. Recent statistical studies of these historical data, as well as observations of the depth of certain temperature-sensitive absorption lines in the photospheric spectrum and balloon and rocket radiometer measurements suggest that variations as large as 0.4 percent of the total flux may occur. These variations, and the smaller changes in total flux implied by the large x-ray, UV, and radio-wave outbursts during flares, have been studied on time scales of seconds to years.

The importance of solar *spectral-flux variations* in restricted wavelength bands (spectral irradiance changes) in controlling the upper atmosphere has been stressed many times. A problem of particular interest is the amplitude of variation in the ultraviolet (UV) continuum over the 11-year activity cycle. These emissions are responsible for the formation and partly for the destruction of atmospheric ozone, as discussed in Chapter 6. It also presents a challenge to solar physics, since it is difficult to construct a physical mechanism that can generate an 11-year variation of the size indicated by the available data.

3. Modern Techniques to Study the Basic Mechanisms of Solar Magnetic Activity

In the last 10 years, advances in our understanding of the basic physics of the sun based on data collected at UV and x-ray wavelengths from space have been matched by equally important advances from ground-based studies. The

interplay of these results with new theoretical insights has substantially altered our ideas about solar oscillations, magnetic fields, and velocity fields, as well as the mechanisms responsible for the supply of escaping plasma and energetic particles and their acceleration and energy balance as they are expelled toward the earth.

The 5-minute velocity oscillation of the solar atmosphere was originally discovered by means of ground-based optical techniques and has been interpreted as standing acoustic waves in the convection zone. The continued investigation into solar "seismology," as it is sometimes called, is well suited to ground-based facilities and should continue to yield productive insights into the depth and structure of the convection zone. Sophisticated optical methods for magnetic-field measurement have revealed that all resolved solar fields are very strong and lie in the range from hundreds to thousands of gauss. Fields of this magnitude can be created on earth only in powerful electromagnets or in laboratory plasma devices such as those used in controlled thermonuclear fusion experiments. These solar fields had been previously thought to be weak because the observations made with low spatial resolution were averaged over neighboring regions of the photosphere that appear to have no field at all.

Recent studies of solar atmospheric motions appear to show an increase in the solar rotational angular velocity in a shallow layer below the photosphere. This result places interesting constraints on the physics governing the rotation of the deepest layers of the convection zone.

An area of central importance to solar-terrestrial research is a continued study of vector magnetic and velocity fields at the highest spatial resolution. This is needed if we are to understand the mechanisms of magnetic-flux intensification, stable containment, evolution through transport, and ultimate dissipation into heat and accelerated particles. Investigation of these phenomena is crucial if we are to continue to move toward a predictive theory of the solar magnetic cycle, the evolution of surface fields to active regions, and coronal holes. To achieve this goal, the detailed study of the dependence of the activity cycle on the coupling of rotation and convection through dynamo action plays a central role.

The construction of a dynamo theory will also require a better knowledge of the large-scale, low-amplitude solar motions in meridional planes and of nonaxisymmetric convective velocity structures predicted by models of rotationally constrained convection. This information is needed before more can be learned about the influence of stochastic variations of heat-flow efficiency to the photosphere, the cause of differential rotation with latitude, and the 22-year magnetic oscillation. There is a distinct possibility that these effects are intimately coupled. We know that they are related to the observed large variations of spectral irradiance observed in the x-ray, UV, and radio-frequency regions of the electromagnetic spectrum over the 11-year cycle. They

may also modulate the total flow of heat to the photosphere and thus influence the solar luminosity.

4. Variable Solar Output of Magnetized Plasma

Studies of the solar atmosphere in the past few years have made impressive advances in identifying and understanding the phenomena and physical processes responsible for modulating the solar output of magnetized plasma and energetic particles. Observations from space vehicles have played the most conspicuous role in increasing our insight, but ground-based techniques, particularly at radio wavelengths, have also been extremely valuable.

Coronal holes were discovered and identified with the long-hypothesized "mystery" regions on the solar surface that give rise to high-speed solar-wind streams that appear to be responsible for increased geomagnetic activity, which recurs at intervals equal to the period of rotation of the sun (27 days). The recognition that the magnetic field lines over the holes diverge more rapidly than radially has also helped to clarify the conditions governing the acceleration of the high-speed solar wind.

The physical factors influencing the formation, evolution, and demise of coronal holes, such as large-scale velocity fields and solar differential rotation, need to be investigated. The development of coronal-hole observations from the ground using the He I 10830-Å line promises to bear on this question.

Recent observations of the corona over the disk at EUV and x-ray wavelengths have allowed us to identify small volumes within the enormous coronal loops that link magnetic regions as the kernels of violent flare eruptions, which accelerate large fluxes of high-energy particles. (See Figure 5.1.) The first direct evidence of nuclear processes at the solar surface has been observed in the gamma-ray lines seen in a few large flares.

Close study of the gas pressure, structure, and dynamics of these magnetic loops, particularly in the EUV, has provided some insight into their layered temperature structure and into the physical conditions required to initiate the plasma instabilities that seem to be responsible for the flare outburst itself.

Majestic configurations of magnetic field and cool plasma perched above the photosphere, which are visible as prominences, sometimes also erupt. These eruptions do not necessarily produce the great heating we see in flares. Nevertheless, these transients also propel enormous volumes of coronal plasma into the solar wind. In a few cases, transients of this sort have been followed from the chromosphere (where they are visible in the H-alpha spectrum line of hydrogen) through the lower corona (at EUV and x-ray wavelengths), well into the outer corona by means of satelliteborne white-light

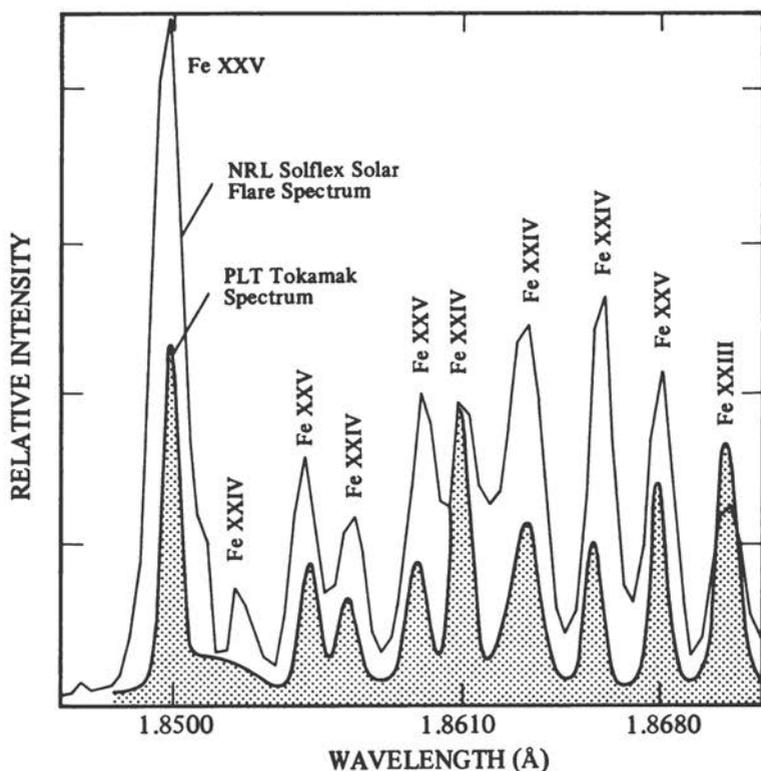


FIGURE 5.1 An x-ray emission spectrum of a solar flare obtained by a Naval Research Laboratory (NRL) instrument aboard satellite STP-78-1 compared with the spectrum of a plasma in the Princeton large tokamak. The spectral lines are associated with transitions in highly ionized iron (Fe XXIII, XXIV, and XXV, with 22, 23, and 24 electrons stripped off, respectively). To produce these ions requires an electron temperature in excess of 12×10^6 K. For the spectra shown here, the flare temperature is 17×10^6 K and the tokamak temperature is 20×10^6 K. The resemblances are striking; the differences are due not to the slight difference in temperature but to the fact that the flare plasma is close to ionization equilibrium, while the tokamak plasma is still rapidly heating up. (Courtesy of NRL.)

coronagraphs and with radio spectral and spatial techniques from the ground and spacecraft.

Solar-wind acceleration in the high-speed streams is thought to depend on dissipation and/or momentum transfer of waves but is not well understood. Observations using the ultraviolet Lyman-alpha coronagraph technique, kinematic studies made with radar, and the analysis of spacecraft telemetry transmissions all promise to be valuable.

The question of coronal heating must be solved in a unified way together with the problem of the coronal mass-balance before we can say that we understand it. Optical observations and UV spectra from rockets show powerful acceleration and heating to coronal temperatures of the material in the network of magnetic fields. The polygonal elements of the network coincide with the interstices between the upwelling cells of supergranulation; the intensified fields in the network are thought to be an accumulation of fields carried from the center to the periphery of each supergranule by plasma flowing radially from the upwelling center to the downflowing cell boundary. It is possible that a powerful ejection process, operating as low as the chromosphere, contributes significantly to the mass and energy supply of the solar wind. The overall questions of mass upflows in spicules, relatively small jets rooted in the magnetic-field network, and their relation to the downflows seen in prominences, loops, and the network itself pose challenging problems for mass and energy transport in the coronal plasma and point to the possible importance of intense electric fields of as yet unknown origin.

Finally, it is of great interest to study the changing configuration of large-scale magnetic fields at the photosphere over the solar cycle. The reversal of polarity of these fields over a 22-year cycle surely influences the magnetic polarity structure of the solar wind near the earth. The relative orientation of the interplanetary magnetic field and the magnetospheric magnetic field is likely to be a factor in allowing magnetic merging (reconnection) between the two fields, thus influencing ultimately the access of solar-wind particles to the earth's atmosphere.

III. THE INTERPLANETARY MEDIUM

1. Introduction

The solar-terrestrial system is physically located within the heliosphere (see Figure 5.2)—a huge bubble in the interstellar gas. This bubble is created by the radial supersonic outflow of plasma from the sun (the solar wind) and its interaction with the interstellar medium. The solar wind expands beyond the earth to the farthest reaches of the solar system to where its momentum flux is balanced by the pressure of the interstellar gas and magnetic field. Pioneer 11, now well beyond the orbit of Saturn, still has not detected this boundary.

Cosmic processes that occur in this vast heliosphere are to a large extent controlled and shaped by this supersonic wind. Hence, the study of the physics of the heliosphere—in all directions and away from the ecliptic plane—is fundamental to an understanding of the cause-and-effect linkage between the sun and earth. We describe below five aspects of research on the

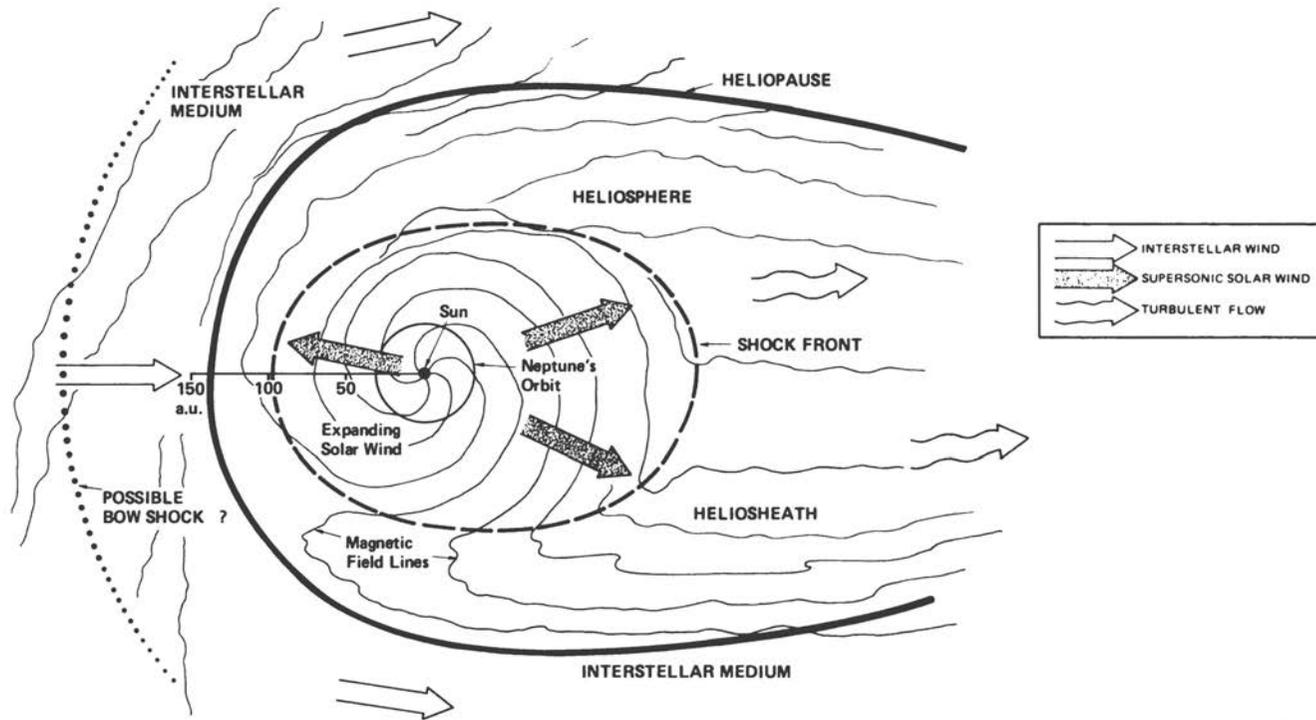


FIGURE 5.2 One possible model of the heliosphere. The plane of the figure is the plane of the sun's equator, which is approximately the general plane of planetary orbits. The details of the outer regions are in doubt: they are based on theoretical extrapolations of the only region (less than halfway out to Neptune's orbit) in which measurements have been made.

interplanetary medium or heliosphere that are currently of central importance to solar-terrestrial research. These are (1) the interface between the sun and interplanetary space; (2) the average structure of the interplanetary medium; (3) transients and collisionless shock waves; (4) basic plasma processes; and (5) energetic particles from the galaxy, the sun, and the interplanetary medium itself.

2. Interface between the Sun and the Interplanetary Medium

Superimposed upon the normal solar radiation incident upon the earth (1.4×10^6 ergs $\text{cm}^{-2} \text{sec}^{-1}$, the so-called solar constant) is the quasi-steady solar-wind energy flux of the earth of some 10^{-1} erg $\text{cm}^{-2} \text{sec}^{-1}$. This estimate includes the kinetic, thermal, magnetic, and potential energy of the solar wind. The outflow is locally interrupted by sporadic solar-flare eruptions in which the magnetic energy resident in intense fields in the chromosphere and corona is suddenly converted into thermal and nonthermal forms in an amount equivalent to about 10^{10} megaton H-bombs. The nonthermal form consists of energetic solar particles that reach the earth at speeds close to that of light. The thermal energy is in the enormous mass ejections that are propelled through the ambient solar wind, preceded by shock waves. Very different from and less violent than solar flares, but potentially equally important to the terrestrial environment, are the high-speed solar-wind streams that emanate from coronal holes, as described above.

At present, we are able to describe the average properties of the solar wind as determined during 20 years of *in situ* observation by spacecraft but do not have a good understanding of the processes responsible for its generation.

3. Average Structure of the Interplanetary Medium

On the smallest scales, the properties of the solar wind are found to be randomly varying and turbulent. At intermediate scales, the dominant features are sharp variations that are encountered along various boundaries. On the largest scales, there is a surprising amount of structure, with gross variations in all directions. The term "average structure" refers to these large-scale features. In the north-south direction, perpendicular to the plane of the sun's equator, the principal asymmetry is associated with the dipole-like character of the solar magnetic field. In the east-west direction (that of the motion of the planets around the sun) variations are associated with solar rotation and fast and slow solar-wind streams.

As the solar wind flows out from the sun, it drags solar magnetic field lines with it. As a direct consequence of solar rotation, the magnetic field is drawn out to form Archimedean spirals on cones of constant heliographic latitude.

Over most of the 11-year solar cycle the magnetic field is now believed to have the basic structure of the Archimedean spiral described above, but with opposite polarities in the northern and southern hemispheres. The signs of the fields change in alternate solar cycles. The oppositely directed fields are separated by a thin current sheet lying roughly in the equatorial plane of the sun. This current sheet (or neutral sheet) is slightly warped so that it extends up to $15\text{--}20^\circ$ above and below the equatorial plane. As the sun rotates, an observer near the earth sees alternately the fields on the north or south sides of the plane. The configuration is sketched schematically in Figure 5.3.

In addition, the solar wind varies in the east-west direction. At any given time, the rotating sun is emitting several fast solar-wind streams, and these are responsible for the structure that is observed in and near the solar equatorial plane. As noted above, it appears that many of these streams emanate from coronal holes on the sun, i.e., the patches in which the coronal luminous intensity and temperature are abnormally low but that are characterized by open magnetic field lines (as described previously) that give those regions relatively unobstructed access to the heliosphere.

When a fast stream overtakes the trailing edge of a preceding slow stream in the interplanetary medium, a characteristic "interaction region" develops (see Figure 5.4). A compression front forms, near which there are large increases in the density and temperature of the solar wind and in the magnitude of the interplanetary magnetic field.

As the solar wind flows beyond the orbit of the earth, a change takes place in the character of the interaction regions, leading to two distinctly different solar-wind regimes. This change is associated with the development of shock waves at the outer and inner boundaries of the interaction regions and the disappearance of the interface. These regions are called corotating interaction regions (Figure 5.4).

As the forward and reverse shocks at the boundaries of the interaction regions propagate beyond the orbit of the earth, the corotating interaction region widens. It appears that when the solar wind reaches 10 to 20 AU, the quiet regions may have been mostly replaced by successive and perhaps overlapping interaction regions, giving rise to persistent irregular variations.

The properties of the solar wind are thought to depend on the solar latitude from which it emanates. There are several lines of evidence that reveal an increase in solar-wind speed with increasing latitude. Spacecraft observations in the ecliptic plane have provided only limited excursions in heliographic latitude ($\pm 7\frac{1}{4}^\circ$) but have demonstrated the existence of this velocity gradient near the solar equator. Ground-based interplanetary scintillation (IPS) measurements have provided indirect evidence of solar-wind behavior at higher latitudes, which have thus far been inaccessible to spacecraft. Thus, exploring the properties of the solar wind at high heliocentric latitudes by means of *in*

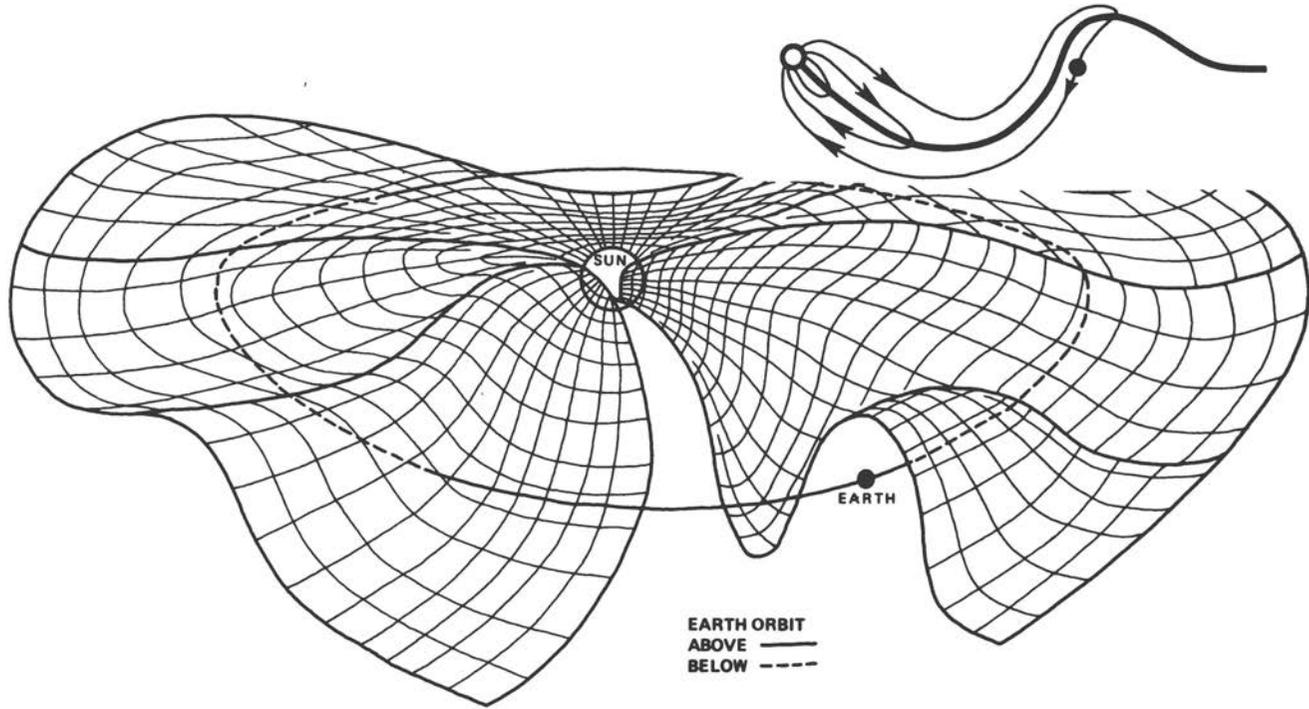


FIGURE 5.3 The so-called “ballerina skirt” model of the solar-interplanetary current sheet. (Courtesy of S.-I. Akasofu, Geophysical Institute, University of Alaska.) The sun is the center of an extensive and warped disk-like sheet in which electric currents flow azimuthally, that is, around the sun. The average plane of the disk is approximately the plane of the equator of the sun’s average dipole magnetic field, which may be tilted with respect to its equator of rotation. The sheet separates solar-interplanetary magnetic-field regimes of nearly opposite or at least greatly different average direction, as shown in the inset, which is a meridional cross section of the current sheet and magnetic field lines on each side.

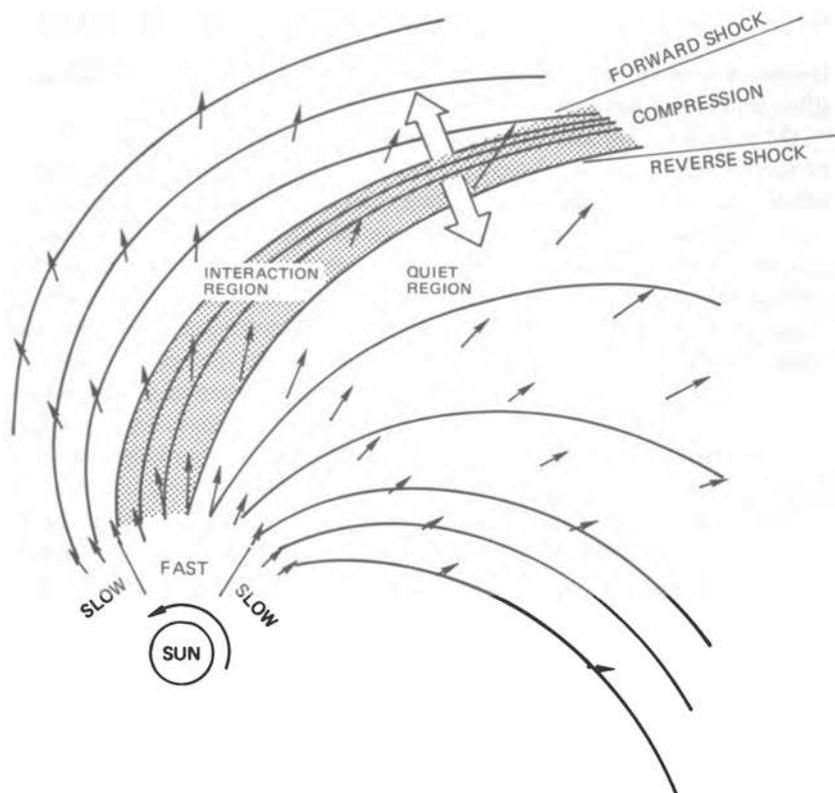


FIGURE 5.4 A corotating interplanetary interaction region. (Courtesy of D. S. Intriligator, USC.) A fast solar-wind stream overtakes and also leaves behind the slower ambient solar wind, thus creating an interaction region in which the plasma is compressed to higher density and temperature. Forward and reverse shocks are also generated.

situ measurements remains an important and exciting task for solar-terrestrial research.

There is a variety of current sheets in interplanetary space about which we know very little. The interplanetary neutral sheet, already mentioned, is only one example, albeit the one probably having the largest scale.

4. Transients and Collisionless Shock Waves

The preceding discussion concerns the average structure of the solar wind. The sun is, however, active and variable, and these variations cause large-scale

transients to propagate out into the interplanetary medium. These transients often generate collisionless shock waves.

On the earth, shocks are encountered as sudden discontinuous jumps in pressure, temperature, and velocity and occur in collision-dominated gases, where the mean-free paths of particles between binary collisions are very small. (Thunder claps and sonic booms are familiar examples.) In interplanetary space, however, the mean-free path between binary collisions becomes large relative to, say, the distance from the sun to the earth. Under these circumstances, the binary collision distances are replaced by much smaller ones, which depend on the collective interactions between the charged particles (ions and electrons) and the broad spectrum of fluctuations in the resident magnetic and electric fields that govern the motions of the charged particles. The net result is a "collisionless" plasma that behaves essentially like an ordinary gas through which shock waves can propagate.

Transient interplanetary shocks are of considerable theoretical interest and are matters of practical concern because they can initiate the onset of magnetic storms. They can also accelerate local solar-wind particles up to subrelativistic energy and deflect galactic cosmic rays and solar particles traveling through interplanetary space.

5. Basic Processes

In addition to the gross, large-scale interplanetary morphology discussed above, the collisionless plasma that constitutes the solar wind is of interest for the study of such fundamental plasma phenomena as heat conduction, turbulence, and wave interactions. Understanding these phenomena is important for a wide variety of physical problems involving astrophysical and terrestrial plasmas, including thermonuclear fusion. For example, magnetic fluctuations that have scales comparable with the scale of the helical motion of the particles in the average (background) interplanetary magnetic field can rapidly change the direction of motion of these particles. The amount of particle scattering is quite dependent on both the types of magnetohydrodynamic (MHD) waves present and their directions of propagation. The problem of describing this wave-particle interaction is a fundamental one in plasma-kinetic theory that has attracted considerable attention during recent years. There remain significant discrepancies between theory and observation, and their resolution requires coordinated theoretical and observational effort.

One of the most important problems in the kinetic theory of the solar wind is that of trying to understand how the flux of heat from the solar corona is carried outward into the interplanetary medium. It was mentioned above that some contemporary fluid models of the solar-wind flow require additional heat sources to account for the observed particle flow speeds and

the electron and proton temperatures. Damping of MHD waves is one attractive possibility. Thus, an understanding of the mechanisms that regulate the electron heat flux is an essential part of any complete picture of solar-wind dynamics. The processes important to this problem are by no means clear. One possibility is that the hot, suprathermal component of the solar-wind electron distribution drifts with respect to the colder thermal component and excites various local plasma instabilities that tend to quench the interaction, thus maintaining a steady state. Other recent work suggests that the magnitude of the electron heat flux may be governed by global effects related to the nature of the large-scale electric fields that drive the solar wind throughout the heliosphere.

Understanding the physics of the regulation of electron heat flux is not solely a solar-wind problem. Heat carried away by the electrons has been shown to be an efficient channel for removing energy from the vicinity of the earth's magnetosheath—a region thought to be the site of significant reconnection of magnetic fields. Thus, it is believed that the key to understanding the coupling of the solar plasma and its magnetic field may be found through studies of the earth's magnetopause, the boundary between the shocked solar plasma and the earth's magnetosphere.

6. Energetic Particles from the Galaxy, the Sun, and the Interplanetary Medium

Energetic particles (nuclei of atoms, electrons) with energies from about 100 keV up to much higher energies pervade the inner solar system and constitute the earth's corpuscular radiation environment. Many of these particles can penetrate deep into the earth's atmosphere and have practical consequences. Some of these particles come from the galaxy, some from the sun, and some from regions in the interplanetary medium. All are influenced by their passage through the heliosphere.

Galactic cosmic rays serve as probes as they are acted upon by the large-scale electromagnetic features of the interplanetary medium that cannot otherwise be observed. Cosmic rays can be studied from space or from the ground. Arrays of ground-based instruments at appropriate locations around the globe constitute directional cosmic-ray detectors that scan the sky as the earth rotates. These provide otherwise unobtainable continuous high-precision observations of relativistic particles ($E > 1$ GeV).

The virtue of studying the motion of galactic cosmic rays as test particles arises from the fact that they come into the heliosphere essentially isotropically, and hence they propagate through regions of high heliocentric latitude still inaccessible to spacecraft. The intensity of these particles varies over a wide range of time scales as conditions change in the solar wind (Figure 5.5).

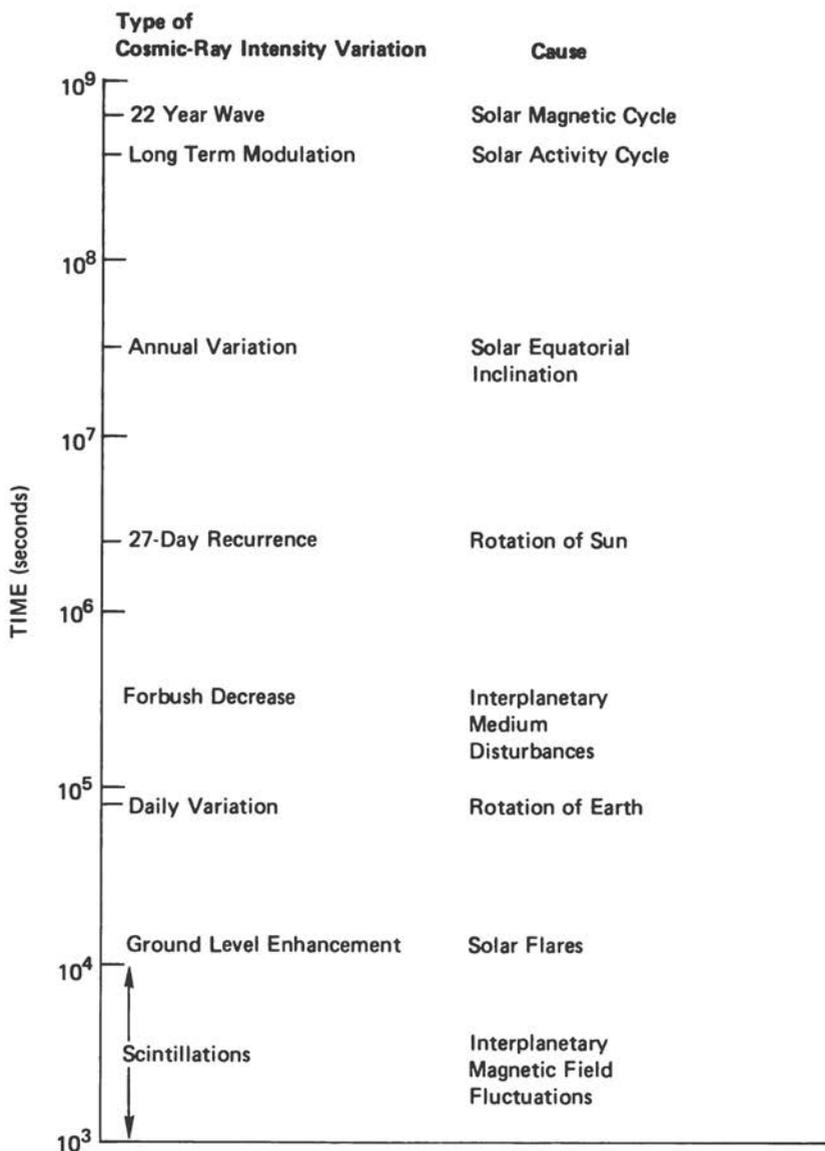


FIGURE 5.5 Types of cosmic-ray intensity variation, their associated periodicity or duration, and their causes. The time in seconds on the scale at left corresponds to the period of the periodic variations and to the approximate duration for nonperiodic events.

Cosmic rays with energies up to ~ 1000 GeV (having a gyroradius of 5 AU in a magnetic field of 5 gammas, or 5×10^{-5} gauss) are affected by the interplanetary magnetic field and hence contribute most to the study of modulation effects.

The physical phenomena that are capable of producing the observed cosmic-ray modulations and anisotropies fall into three general categories:

1. Large-scale convection, diffusion, drift, and adiabatic deceleration;
2. Motion of boundaries through the interplanetary magnetic field;
3. Coherent particle drifts over large distances in the interplanetary magnetic field.

While the galactic cosmic rays discussed above are the dominant particles at high energies (above about 100 MeV), other particles released from the sun or escaping from the earth and Jupiter populate the lower-energy range of the spectrum. It is generally believed that shock waves are capable of accelerating these particles, both at the sun and in the interplanetary medium. For example, it is known that the bow shock in front of the earth's magnetosphere often accelerates particles to energies of ten to hundreds of keV; these so-called "upstream" particle bursts have been detected several hundred earth radii (several million kilometers) upstream of the earth's bow shock. Shocks associated with corotating interaction regions (CIR's), which are often formed beyond the orbit of the earth (see Section 3 above), accelerate particles to energies as high as 10 to 20 MeV/nucleon. Shocks formed when a fast solar-wind stream, generated at the time of a solar flare, overtakes the slower ambient solar wind, accelerate particles locally to energies of hundreds of keV.

As noted in Section II above, the sun frequently accelerates and releases into the interplanetary medium energetic particles with energies up to a few hundred MeV. Much less frequently, solar particles with energies extending up to the GeV range are observed. Jupiter is now also known to be a strong source of electrons (with energies ranging from a few MeV to tens of MeV), which are easily observed near earth and are known to stream both toward and away from the sun. There is some evidence that the earth may also be a source of sub-MeV protons, and it is possible that some of the energetic ions found in the Jovian magnetosphere may leak out and contribute to the overall energetic-particle population of the interplanetary medium.

An observer, at a given location in the heliosphere at any given time, will therefore detect energetic particles from a number of different sources. The relative contributions of the various sources of energetic particles will change with time as well as with the location of the observer.

IV. THE MAGNETOSPHERE-IONOSPHERE SYSTEM

1. Introduction

The earth's magnetosphere arises from the interaction of the solar wind with the planet's intrinsic magnetic field. The magnetosphere is a cavity carved out in the solar-wind flow. Inside this cavity the planetary magnetic field dominates and organizes the behavior of charged particles, plasma waves, and electric currents. It also traps energetic particles, confines low-energy plasma, and transports hydromagnetic stress from the magnetosphere (via the partially conducting ionosphere) to the upper atmosphere of the earth.

Through work in the recent past, including that encouraged and supported by the International Magnetospheric Study (IMS), research on the earth's magnetosphere has delved into some of the problem areas of most fundamental concern to laboratory and astrophysical plasma research. While concepts of basic plasma physics are important to any understanding of the microscopic and macroscopic plasma (and thus energy) transfer throughout the magnetosphere-ionosphere system, the earth's plasma environment cannot be decoupled from its geophysical context. Thus, concepts of fundamental atomic and chemical physics are required for understanding the interface between the plasma system and the neutral atmospheric gases. For a number of significant problems associated with waves and ionospheric currents, concepts in solid-earth geophysics, planetary magnetism, and geoelectricity are needed. Thus, research in magnetospheric-ionospheric processes serves as a link in the broad discipline that we call geophysics.

The developing understanding of our space environment from the IMS shows that the magnetosphere-ionosphere system also serves as an important link in the energy transfer from the sun to the earth.

The solar-energy output in the form of fields and particles is transported through, and altered by, the magnetosphere-ionosphere system before most of it is deposited in the upper atmosphere of the earth. Variations in the solar particles and fields produce significant variations in the state of the magnetosphere-ionosphere system.

Described below are the regions of the magnetospheric-ionospheric system that are of central importance to solar-terrestrial research. These areas are (1) the bow shock and magnetopause and (2) the plasma, fields, and waves within the magnetospheric cavity. The latter provides another laboratory for the study of basic plasma processes, but with conditions or parameters (scale size, field strength, and kinetic and thermal energy, for example) that are different from the interplanetary medium.

Following these two discussions, a number of scientific problems of high current interest are outlined in order to illustrate some frontier areas of research in this field.

2. Bow Shock and Magnetopause

The shock wave "announces" to the approaching solar wind that an obstacle will be encountered in its hitherto unimpeded flow. Between the shock wave and the magnetosphere the shocked solar-wind flow becomes more turbulent as it approaches and flows around the magnetosphere boundary. The magnetosphere boundary is a dynamic (i.e., nonstationary) region where the shocked solar-wind plasma and its associated magnetic field constantly interplay with the planetary magnetic field and confined magnetospheric plasma.

The plasma in the solar wind and its associated magnetic energy must enter the magnetosphere proper by fundamental plasma processes that are not yet known or understood. The steady flow of the solar wind around the boundary generates a large-scale electric field across the entire magnetosphere. This electric field causes plasma in the nightside of the magnetosphere (the magnetotail) to flow toward the earth.

Data exist that show that certain orientations of the interplanetary magnetic field lead to enhanced transfer of solar-wind energy into the magnetosphere and/or energy release in the magnetosphere. Changes in the solar-wind plasma pressure on the magnetosphere boundary produce similar effects. These periods of enhanced activity are called "magnetic storms" (or "substorms" for smaller events). These are periods when the magnetic field measured at the earth's surface fluctuates considerably.

A planetary magnetosphere involves a system of many distinct, mutually interacting plasma regimes: the streaming solar wind, the premagnetosphere shock wave, the magnetosphere boundary, the collisionless plasma confined in the magnetospheric cavity, and the resistive plasma of the ionosphere, which is collisionally tied to the neutral atmosphere.

Multiplasma environments of widely different scale sizes and complexities also exist in astrophysical systems. An active sunspot region is an example of a small-scale system, and radio galaxies are cosmic-scale systems. In fact, in astrophysics the concept of a "magnetosphere" has now been generalized to designate any plasma envelope around a compact magnetized central body.

3. Plasmas, Fields, and Waves in the Magnetospheric Cavity—A Laboratory for the Study of Basic Plasma Processes

A fundamental property of a magnetospheric system is its ability to transport energy from one plasma regime to another—in the case of the earth, from the solar wind through the magnetospheric boundary to the ionosphere and upper atmosphere. This coupling controls the energy and momentum deposition into the earth's upper atmosphere. It is through this process that many perturbations associated with solar activity, i.e., those transmitted by the solar wind, are transduced into effects detectable on man-made systems on

the ground, in the atmosphere, and in near-earth space. Finally, it is through this magnetosphere-ionosphere-atmosphere coupling that some physical mechanism should be sought that may be responsible for possible effects of solar variability on the lower atmosphere, weather, and climate.

Magnetospheres and multiplasma systems often exhibit an ability suddenly to release gradually accumulated magnetic energy and thereby convert it into organized, nonthermal energy of charged particles. On the sun, this process of high-energy particle acceleration is called a solar flare; on earth and Mercury, a magnetic storm (or substorm for smaller events). In astrophysical magnetospheres, particle acceleration to relativistic energies is manifested by the electromagnetic radiation emitted by these particles. Galactic cosmic rays may likewise be the result of an acceleration process, or chain of processes, in a multiplasma system. The study of such universal acceleration mechanisms is obviously of fundamental importance to the quantitative understanding of the solar-terrestrial chain of energy transfer, in which they participate so significantly.

The earth's magnetosphere offers the opportunity to study *in situ* the related energy storage and release mechanisms and their microscopic properties responsible for particle acceleration. Other solar-system planetary magnetospheres (see Section VI of this chapter) are now also accessible to *in situ* probing, although not in the same detail as the earth's; thus, a wide range of magnetosphere scale sizes ranging from the "minimagnetosphere" of Mercury to the "macromagnetosphere" of Jupiter is available for comparative study.

In quite a different area, a magnetosphere with its multiplasma regions separated by discrete boundary layers generates a host of plasma instabilities and nonlinear phenomena that regulate the energy, momentum, and mass-transfer processes from one region to the other. These processes and the acceleration processes mentioned above constitute basic physical phenomena that are equally interesting to laboratory plasma physics. Fundamental plasma topics include magnetic-field reconnection, the interaction of turbulence with magnetic fields, and particle confinement and transport.

4. Scientific Problems

(a) Global Processes

Several specific global (as opposed to localized) topics in magnetospheric-ionospheric research are discussed below to illustrate some general problems of greatest scientific interest at present (see Figure 5.6).

(i) *Origin and Fate of Magnetospheric Plasma* Plasma is found in all regions of the earth's magnetosphere. After two decades of satellite exploration,

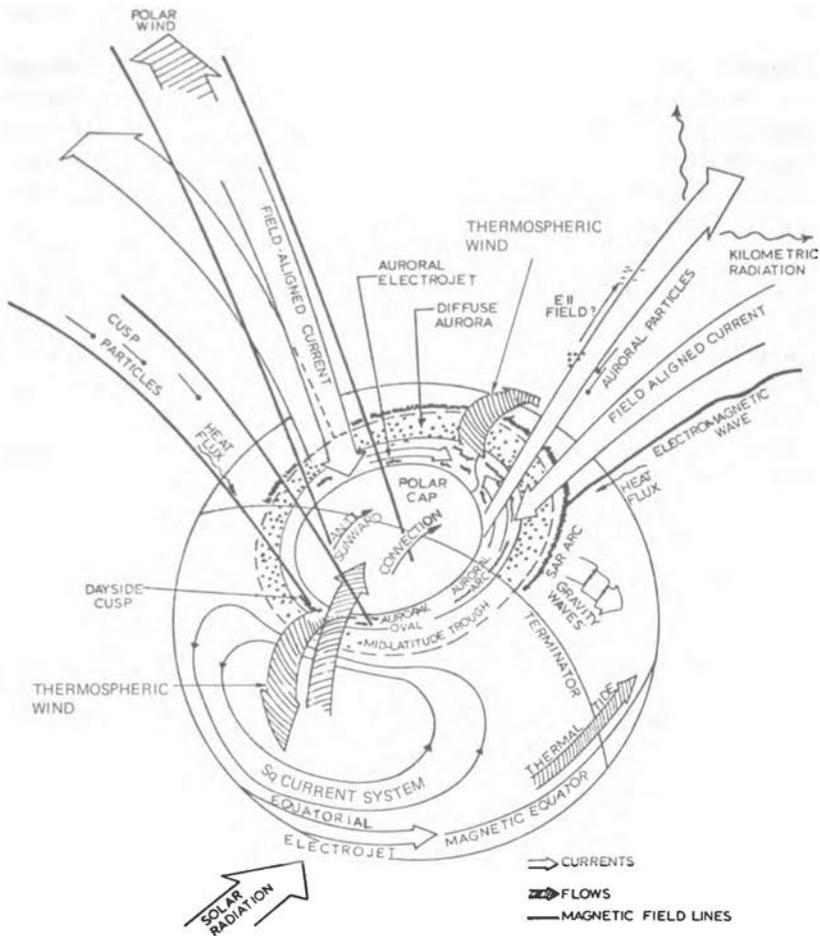


FIGURE 5.6 A selection of some principal magnetospheric-ionospheric-atmospheric phenomena.

many distinct plasma domains have been identified and distinguished by observed physical characteristics and/or theoretical “expectations.” These domains, often not independent, include the polar cusps, plasma mantle, plasma sheet, entry layer, plasmasphere, and ring current. It is the topological and dynamical relationships among the plasma domains that pose some central questions for the next decade.

Magnetospheric plasma originates from two intrinsically distinct sources: the earth’s ionosphere and the solar wind. Ionospheric plasma is created

principally from the ionization of the upper atmosphere by short-wavelength solar electromagnetic radiation (see below); this plasma includes particle species such as hydrogen, helium, nitrogen, oxygen, and electrons. The solar wind consists principally of ionized hydrogen and helium, as well as electrons.

Certain magnetospheric properties or events are causally associated primarily or exclusively with one plasma source. Other events are more complex and involve more than one plasma source. As an example of a one-plasma regime, the plasmasphere is low-temperature, high-density plasma that occupies the inner magnetosphere and represents the extension of the ionosphere into space. It is confined by magnetic shells or tubes of flux of the earth's field and is usually quite distinct from the more energetic plasma in the surrounding outer magnetosphere. By contrast, the commencement of a magnetic storm, caused by the disturbed solar-wind plasma impacting the outer magnetosphere, involves at least two regimes. The main phase of the magnetic storm is even more complex. Here the magnetospheric plasma is mixed with solar wind and ionospheric plasmas resulting from direct injection of plasma from the geomagnetic tail and the acceleration of heavy ions upward out of the ionosphere.

Measurements have recently been reported of the electric fields that exist parallel to the magnetic field in the auroral regions at altitudes of a few thousand kilometers. These electric fields undoubtedly arise through microscale processes in the magnetospheric plasma. The electric fields are thought to be the agent that accelerates plasma out of the ionosphere and causes magnetospheric plasma to be deposited into the upper atmosphere, enhancing the ionization there. Such field-aligned currents can drive ionospheric currents on a global scale and provide a possible explanation, for example, for the correlation of ground-based magnetic observations at the equator and at auroral latitudes.

To summarize the fate of magnetospheric plasma: Magnetospheric plasma, once created or captured, is either lost or "permanently" stored. Loss processes fall into two categories: the return of plasma to the solar wind or to the earth's atmosphere. Loss to the solar wind can occur by plasma escaping across the magnetopause or by ejection down the geomagnetic tail. Under certain conditions plasma can also be stored in the magnetosphere for long periods of time (as long as many years in the case of the radiation belts).

Several questions relate to the plasma sheet and its topological connections to the polar cusp, the boundary layers, and the aurora. For example, the morphological characteristics and ion compositions of the aurora and plasma sheet suggest a direct connection between the two, but the issue is not resolved. Furthermore, understanding the nature of the auroral substorm continues to pose great difficulty as the complexity of the problem grows more rapidly from the accumulating observational evidence. The boundary layer

may have easier access to the plasma sheet than other regimes, but this suggestion is speculative.

The entry layer at the subsolar point (i.e., at the nose of the magnetosphere) is characterized by diffusion processes and large pressure gradients. The latter may play a role in driving plasma into the boundary layer on the flanks of the magnetosphere. These regions of the magnetosphere require far more study.

Study of the polar cusp regions deserve emphasis and will undoubtedly lead to many discoveries in the next decade. Properties of dayside aurora, polar-cap phenomena, and the degree of turbulence in the cusp regions all require further study. Magnetic merging (see below) is a process that has not been unambiguously confirmed (but is nevertheless invoked to explain many magnetospheric phenomena); it may occur in the cusp regions.

(ii) *The Aurora* Where the aurora occurs and why it occurs at the locations it does are questions that have received much attention throughout this century, beginning with the pioneering Arctic expeditions of Birkeland and Stoermer's calculations of the motion of a charged particle in a dipole geomagnetic field. Today, a great deal is known about where the aurora occurs, and certainly it is understood why it occurs. The aurora occurs in both hemispheres at high latitudes in oval-shaped zones. The auroral zones may at times extend a full 360° around the geomagnetic poles or may at times concentrate principally on the nightside. The aurora is caused by the precipitation of particles (principally electrons and protons) of magnetospheric origin, which collisionally excite atoms in the upper atmosphere. The excited atoms return to their ground or normal state through the spontaneous emission of light that constitutes the aurora. There are many morphological characteristics of the aurora that have been carefully measured and cataloged.

Most early work on the aurora was based on visual observations, whereas more recent studies have utilized far more sensitive ground-based photometric observations, satellite imaging and particle data, radar observations, and other techniques. Interpretation of the early visual data was mostly of a statistical nature. By contrast we are now able to study individual auroral events and make detailed comparisons with other magnetospheric measurements. Thus, in posing the question of the origin of the aurora we now include the identification of the source of the precipitating particles, the particle precipitation and energization mechanisms, and an accounting for the time scales of events (e.g., the recovery time of a magnetic storm or of a substorm).

The task of understanding the location of the aurora is no less complex. Earlier morphological studies established where the aurora occurred on a global scale, and associated correlation studies established that variations in location are very large and commonplace. Many unanswered questions

remain. We still do not understand why the poleward boundary of the aurora is so much more variable than the equatorward boundary, or what dynamical factors control these boundaries. The dynamical (physical) connection between the incidence of auroras and the orientation of the interplanetary magnetic field, which correlation studies indicate may be related, is also not fully understood. Only recently, on the DMSP satellites, have concurrent measurements become available of the spectrum of precipitating particles and the resultant auroral images. The novel imaging experiments on the forthcoming Dynamics Explorer mission promise to provide unprecedented coverage in space and time of auroral occurrence and the development of auroral substorms.

Advancing our knowledge of the nature of auroras will require the development of better theoretical models and the acquisition of observational evidence for the extension of the aurora upwards into space. The dynamics of the region inside the auroral oval (called the polar cap) will be a central issue. Here electric fields of magnetospheric origin control the motions of ionospheric particles; models for this effect are still extremely elementary and ignore much of the growing base of observational information. The location of field-aligned currents within the auroral zones, the microstructure of electric and magnetic fields within arcs, across zones of field-aligned currents, and in the polar cap all require additional observational and theoretical study. More comprehensive electric-field measurements along magnetic field lines are needed to trace the origin of particles and energization processes more conclusively.

(iii) Mass Coupling between the Magnetosphere and the Atmosphere The principal constituents of the magnetosphere are hydrogen, helium, and oxygen ions, whose origins can be traced either to the photoionization of gases in the earth's upper atmosphere or to the entry of solar-wind plasma. Near the earth, charge exchange between ionospheric oxygen ions and atomic hydrogen provides a ready source of protons which fill the low-latitude magnetic flux tubes to form the plasmasphere.

Above about 60° magnetic latitude the magnetospheric convection electric field acts to transfer ionospheric plasma to magnetic field lines, which connect into the magnetosphere tail. The result is the polar wind, a high-speed, outward flow of low-energy protons and helium ions with a net plasma density a factor of approximately 1000 lower than the ion densities in the plasmasphere.

A separate magnetospheric source of oxygen and helium ions is found at altitudes above discrete auroras. Through a mechanism that is not yet understood, ionospheric oxygen and helium ions are heated and accelerated away

from the earth along magnetic field lines that connect to the aurora. The fate of these ions is not known as yet; it is possible that the hot oxygen ion component may play an important part in the dynamics of the ring current.

A number of outstanding unsolved problems exist concerning mass couplings in the magnetosphere. These include the determination of (a) the fraction of the polar wind ultimately lost from the magnetosphere, (b) the role of energetic ions in the overall dynamics of the magnetosphere, (c) the contribution of the plasmasphere to the overall mass budget of the magnetosphere, (d) the extent to which the solar wind may provide a source of magnetospheric plasma and rare elemental species in the atmosphere, and (e) the validity of classical diffusion theory as an accurate explanation for the high speed of the polar-wind flow.

(iv) Transport of Energy and Electric Fields from High to Low Latitudes
Joule heating and particle precipitation at auroral latitudes are important sources of energy for the thermosphere, as well as perhaps the upper mesosphere. These localized heating sources launch gravity waves that propagate to lower latitudes and also produce meridional circulation patterns that significantly alter the undisturbed global thermospheric wind pattern. As a result of this perturbed meridional circulation, thermospheric temperatures and compositions can be significantly altered on a global scale during disturbed magnetic conditions. The altered thermospheric conditions change electron densities in the ionosphere. These processes are discussed further in Section E.

Magnetospheric electric fields seem largely confined to high geomagnetic latitudes but can penetrate to low latitudes, where they affect the dynamics of the plasmasphere and plasmopause, the ring current, and the ionosphere. The efficiency with which high-latitude electric fields penetrate to lower latitudes depends on the distribution of ionospheric conductivity as well as on the rates of change of the electric fields themselves. Their variations arise from the tendency of the inner edge of the plasma sheet to shield lower latitudes from the steady, high-latitude convection field. However, more rapidly varying substorm electric fields are observed well inside the plasmopause. Transient electric fields associated with interplanetary magnetic-field changes have been observed in the equatorial ionosphere. A fuller understanding of this process requires a more complete picture of the global electric circuit.

(b) Scientific Topics Regarding Localized Processes

The following research problems of considerable current interest have been selected as examples of localized processes.

(i) *Plasma Boundaries* A number of distinct boundaries between plasma regimes have been identified in geospace. These boundaries include the plasmopause, the magnetospheric boundary (magnetopause), and the bow shock of the magnetosphere. The plasmopause marks the boundary between the region where the plasma motion (flow) is dominated by the corotational electric field of the earth and the region where it is dominated by the large-scale magnetospheric convection electric field. The magnetopause is formed by the interaction of the solar-wind plasma with the vacuum magnetic field of earth. The physical role that the magnetic field in interplanetary space plays in the formation of the earth's magnetopause remains poorly understood and is an area of active investigation in magnetospheric science. The bow shock, sunward of the earth's magnetopause, is produced by encounter of the supersonic solar wind with the obstacle of the earth's magnetic field.

In recent years considerable understanding has been achieved in studies of the collisionless bow shock upstream of the earth's magnetopause. The investigation of the earth's magnetopause has continued, most recently by use of the dual ISEE spacecraft to separate spatial and temporal variations at the boundary. Studies of the plasmopause have furnished new information on the trapping and losses of ions and electrons and the generation of waves at an internal boundary.

Much work remains to be done in understanding the nature of the earth's magnetopause. The interaction of a magnetized plasma (e.g., the solar wind) with a vacuum magnetic field remains a fundamental plasma problem. Not only is the interaction at the earth not understood, but the magnetopause structure of Jupiter appears to be quite different from that of the earth. The collisionless bow shock requires still further investigation, particularly its role in producing waves and energetic particles upstream (sunward) from the bow shock. The effects of the plasmopause in the generation of hydromagnetic-wave phenomena in the magnetosphere and in producing particle precipitation requires further work. In summary, plasma boundaries in the geospace environment represent some of the most interesting plasma phenomena that are produced by the interactions of magnetic fields and plasmas of quite different characteristics. Studies of these boundaries in a cosmic environment will continue to contribute to understanding of laboratory plasma boundary phenomena.

(ii) *Origin, Configuration, and Role of Electric Fields* The dc and quasi-dc electric field has only in recent years become one of the fundamental observables of the magnetospheric plasma system. Commonly, in magnetosphere research, if the physical process responsible for the field (its "origin") is external to the plasma region under consideration, the electric field can be viewed as "driving" the plasma's bulk motion. On the other hand, if the

plasma's bulk motion is impressed by external forces (e.g., collisional or turbulent friction), the electric field is viewed as "induced" by the plasma motion (dynamo electric field "originating" in the moving plasma).

In addition to the perpendicular electric field (E_{\perp}) discussed above, there are often parallel electric fields (E_{\parallel}) in some regions of the magnetospheric plasma. Any E_{\parallel} will be uncoupled from the bulk plasma motion. An E_{\parallel} can appear on a macroscopic plasma scale under several possible conditions: in the presence of (1) a field-aligned current whose particles experience a finite resistivity (e.g., electrostatic and electromagnetic plasma waves), (2) ions and electrons with different distribution functions (double layers), (3) current-driven electrostatic shocks, or (4) as a component of an induction electric field.

The magnetosphere is bounded on one side by the resistive ionosphere, which is embedded in a neutral gas that can impress its own motion on the plasma (creating dynamo E fields), and on the other side by its interface with the solar wind. It is believed that the combined effect of, and interplay between, the boundary and ionospheric dynamos determines the large-scale quiescent convection in the magnetosphere and the configuration of its "open" (convection proper) and "closed" (corotation) regions.

Progress has been made in recent years in the study and understanding of this system of quiescent, large-scale convection and its implications for energetic particle motion, the formation of the plasmasphere, and some dynamic properties of the magnetospheric tail during magnetically quiet times. A sequence of causal relationships is generally accepted: (1) The solar-wind dynamo impresses an electric field onto the open-field-line region of the magnetosphere; (2) this region, connected to the polar-cap ionosphere, determines the electric field therein; (3) given the polar-cap field, the ionospheric conductivity electrostatically determines the electric field equatorwards of the polar-cap boundaries; (4) this, plus the corotation dynamo, determines the electric field in the entire closed-field-line domain.

Many questions related to the magnetospheric electric fields remain. For the quiescent electric fields, these questions concern (1) the relative importance of the dynamo in the boundary layer and any magnetic-line interconnection between the interplanetary and magnetospheric fields and (2) the small-scale mechanisms responsible for the boundary dynamo. Two other questions concern (3) the mechanism(s) by which electric fields, impressed on the polar-cap ionosphere, are "transmitted" to lower latitudes and (4) coupling between the ionospheric-magnetospheric electric field and that in the troposphere-stratosphere, which were discussed in Subsection IV.4.a(iv) above, has local as well as global aspects. Quantitative information on transient electric fields in the magnetosphere is almost completely lacking. Information and theory are needed for understanding the electric field acting on

auroral-zone field lines at altitudes of several thousand kilometers, for understanding the nature and onset of instabilities in the cross-tail current, and for understanding the physics of magnetic field reconnection (see the following section).

(iii) *Magnetic-Field Reconnection* Magnetized plasma regions containing two domains with differently directed magnetic fields in contact with each other that are pushed together tend to develop a thin layer of plasma at the contact boundary containing intense electric current sheets. The magnetic equatorial plane of the magnetotail is such a region. Such current sheets can also exist in interplanetary space at sector boundaries and tangential discontinuities and in the solar chromosphere and corona.

Theoretical studies, analytical as well as computer simulations, suggest that the reconnection process involves a complex interaction between macroscopic and microscopic plasma processes. The large-scale plasma flow and magnetic fields (i.e., the "boundary conditions") appear to control the overall dynamics and energy conversion rate. In the small region surrounding the magnetic null, electric current-driven plasma turbulence (microstructure phenomena, see above) may operate together with inertial and/or collisional processes to produce a resistivity in the null region.

The applicability of reconnection to magnetospheric processes, and to astrophysical systems as well as to laboratory devices, is far from proven. Much work is needed in such areas as (a) theoretical and computer simulation studies of two- and three-dimensional systems, (b) laboratory experiments to study plasma properties at the resistive limit, and (c) magnetosphere observations designed to resolve the spatial and temporal effects of plasma and field movements that may be associated with the reconnection process.

(iv) *Acceleration and Heating Mechanisms* It now seems clear that in the auroral region the "frozen-in" magnetic-field concept, derived from basic magnetohydrodynamic theory, is not completely valid. Magnetic-field-aligned potential drops occur that dissipate energy through the acceleration of charged particles; Figure 5.7 is a schematic representation of our contemporary concept of the physics in such a region of the magnetosphere, in which electric fields are aligned with the magnetic fields. This picture comes from the interpretation of low-altitude auroral particle measurements (made with rocket flights) and optical observations of the motion of auroral forms. Barium releases from rockets and Skylab were also useful in revealing upward ion acceleration. A Department of Defense spacecraft made the first *in situ* measurements of electric fields in the acceleration region.

During magnetic storms, energetic ions and electrons appear in the trapping region of the magnetosphere. Electrons are accelerated to energies as

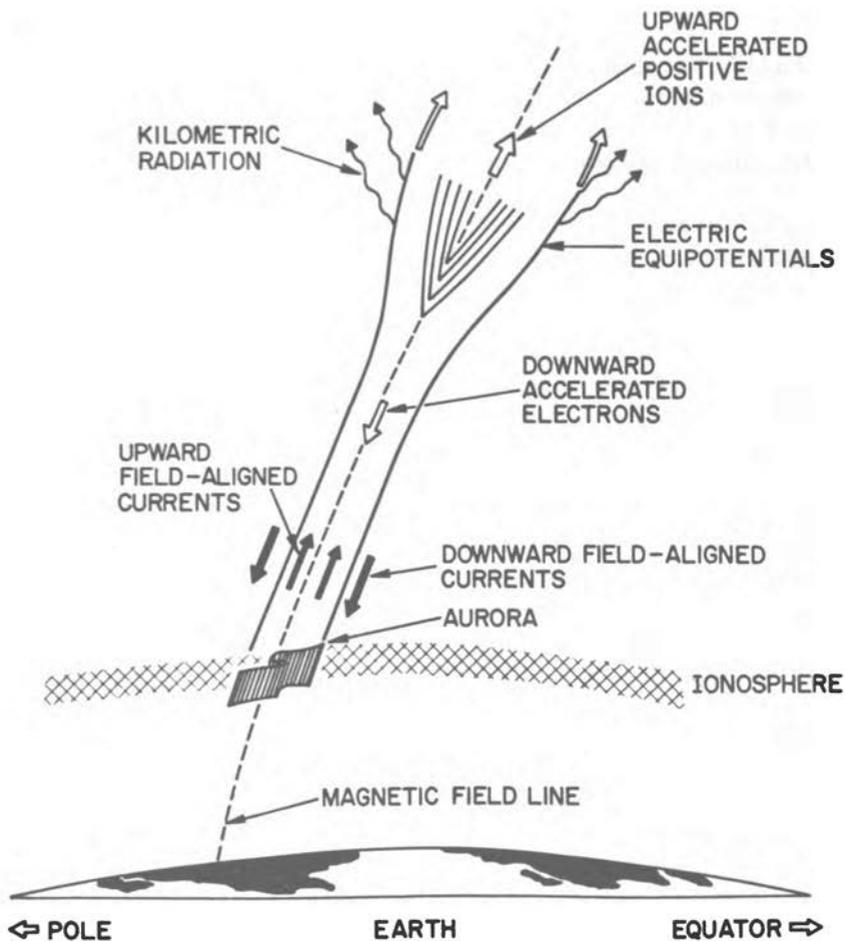


FIGURE 5.7 Schematic meridian cross section through the auroral oval, showing the structure of aurora-associated electric currents and fields aligned with the geomagnetic field. (Courtesy of L. J. Lanzerotti, Bell Laboratories.)

high as several MeV. The appearance of these particles often occurs within a time span of a few minutes or less, generally on the nightside of the magnetosphere, although cases have been reported on the dayside. While such particle enhancements have been noted since the earliest days of magnetospheric research, our understanding of their dynamics is far from complete. Adiabatic processes such as betatron acceleration, and plasma instabilities such as drift waves, have been used to explain the apparent acceleration.

Fundamental theoretical and observational work is needed to understand acceleration processes in the magnetospheric plasma. Some of the work should include (a) a determination of the altitudes and time dependencies of auroral field-aligned acceleration regions; (b) the geophysical conditions for the onsets of such currents; (c) plasma processes that produce energetic trapped particles; and (d) the relationships, if any, between accelerated trapped particles and particles accelerated at low altitudes above the auroral zone.

(v) *Origin of Plasma Waves* The term "plasma waves" characterizes all those waves that can propagate in a plasma or that have their wave characteristics significantly modified by the presence of a plasma. Plasma waves can be predominantly electromagnetic (having both electric and magnetic fields produced by current fluctuations) or electrostatic (having only an electric field produced by fluctuations of electric charge). Hydromagnetic waves are plasma waves that exist only in highly ionized, magnetized media such as solar-system plasmas. Most plasma waves are generated by the conversion of plasma and energetic particle kinetic energy into wave energy through a variety of wave-particle interaction processes. In turn, these waves may interact with the particles and modify the velocity distribution of particles in the plasma.

Regions with significant plasma-wave activity in the earth's magnetosphere are schematically illustrated in Figure 5.8. A number of the observed VLF emissions (10 Hz to 30 kHz) have been attributed to amplification through the interactions between coherent particle beams and plasma waves. Particle dynamics of the trapped radiation belts are determined by some of these waves. Kilometric radiation (50-500 kHz) observed above the auroras appears to be related to the auroral particle acceleration and may be comparable to the radio emissions observed from the outer planets. Electrostatic noise is frequently detected in regions containing hot or streaming plasma. Waves and noise in the hydromagnetic frequency regime are observed throughout the magnetosphere and are often enhanced at boundaries such as the plasmopause.

Several outstanding problem areas in understanding plasma waves include the determination of (a) the conditions for generating electrostatic waves and their consequences; (b) mechanisms for generating the earth's kilometric radio bursts (and radio bursts from Jupiter, Saturn, and Uranus); (c) the roles of plasma waves in energetic particle dynamics; and (d) the sources of low-frequency waves and noise in the terrestrial magnetosphere.

(vi) *Electric Coupling between Magnetosphere and Atmosphere* Recent evidence suggests that strong electrical coupling exists between the ionosphere

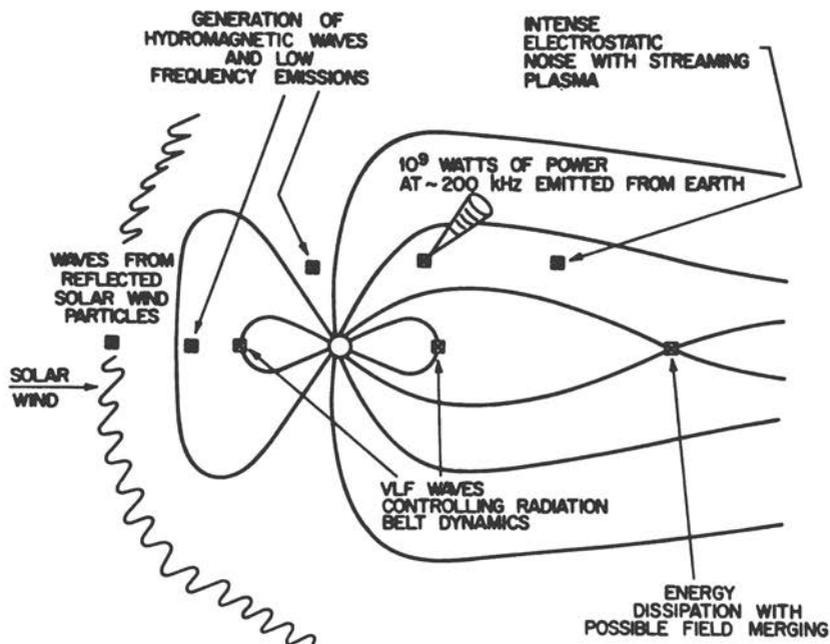


FIGURE 5.8 A schematic noon-midnight section of the earth's magnetosphere showing regions with significant plasma-wave activity. Compare with Figure 1.3 in order to identify the locations mentioned below.

and the lower atmosphere. Large-scale horizontal electric fields of magnetospheric and ionospheric origin map down, with little attenuation, to an altitude of about 10 km. The total potential drop across regions like the polar cap and the auroral ionosphere can be a significant fraction of the average ionospheric potential with respect to the earth (240,000 V). Thus, the magnetospheric-ionospheric electric field can significantly affect the global distribution of the vertical fair-weather field near the earth's surface. The atmospheric electric field also depends on the conductivity distribution within the atmosphere, which is known to be modulated at various altitudes by electron precipitation during magnetic storms and by solar-flare x rays, solar proton events, and galactic cosmic-ray variations. These questions naturally interest atmospheric physicists and meteorologists as well.

Model calculations indicate that electric fields from large thunderstorm systems in the atmosphere may reach the ionosphere and magnetosphere with sufficient intensity to have important dynamic effects. They can affect plasma ducts and ion dynamics in the magnetosphere.

Several important considerations for further elucidating the electrical coupling processes within the earth-atmosphere-magnetosphere system include (a) a study of the solar-terrestrial influences on atmospheric electric fields by simultaneous measurements on the ground, in the middle atmosphere, and in the ionosphere; (b) determination of the role of electric fields in transmitting disturbances vertically between regions; and (c) determination of the role, if any, of mapped magnetospheric electric fields in modulating thunderstorms in some latitude regions of the earth.

(vii) Ionospheric Dynamics The global-scale convection electric field strongly influences the properties of the ionosphere. At high altitudes, in the F region, where ion-neutral collisions are infrequent, the ionospheric plasma has a pattern of $E \times B$ drift velocity that extends over the entire polar cap and down to magnetic latitudes of 60° . Because of competing photochemical and dynamical effects, the ionospheric structure is quite complex. At low altitudes (in the ionospheric E region) additional ionospheric complexities can arise from a coupling of electrodynamic effects involving the relation between plasma motions and electrical conductivity. Such effects are of particular importance in the ionosphere near the plasmapause, where very large convection electric fields can appreciably reduce the ionospheric conductivity and modify the driving magnetospheric currents.

Several important problem areas involving ionospheric dynamics include (a) a determination of whether plasma convection at ionospheric heights is similar to that farther out in the magnetosphere, (b) a determination of the atmospheric species by-products of ionospheric convection at high latitudes, and (c) further studies of current theoretical models to determine if they can predict the gross features of high-latitude plasma densities.

V. THE ATMOSPHERE

1. Introduction

The region of the earth's atmosphere from an altitude of about 10 km (the tropopause) to near 90 km (the base of the thermosphere) encompasses the stratosphere and the mesosphere; in recent years this region has become known as the middle atmosphere. The thermosphere is considered to extend from 90 to about 500 km altitude and includes the ionosphere. The thermosphere and the middle atmosphere are sinks for almost all of the known large variations in solar energy, i.e., the energy in the electromagnetic spectrum between about 10 to 2000 Å and the energy of the solar particles and the interplanetary magnetic field that constitutes the solar wind.

The middle atmosphere absorbs solar electromagnetic energy at ultraviolet (UV) wavelengths (2000–4000 Å), galactic cosmic rays, energetic solar protons, and particles accelerated within the earth's magnetosphere whose intensities are modulated by the solar-controlled interplanetary medium. The shorter-wavelength extreme ultraviolet (EUV) solar radiation is absorbed largely in the thermosphere, as are x rays produced by solar flares.

Described below are these two regions of the atmosphere where research is of central importance to solar-terrestrial research.

2. The Thermosphere

We shall encounter two problems in this description. The first problem is that, just as the ionosphere and magnetosphere are linked by electrodynamic and particle transport, so are the neutral atmosphere and ionosphere linked by electrodynamic and momentum transfer, so that some phenomena described here are either identical to or extensions of phenomena described in Section D above, perhaps from a slightly different point of view. The second problem is that such aspects of the upper atmosphere as its composition, chemistry, energetics, dynamics, and resulting structure, which are functions of location and time, are all so intricately interrelated that it is not really possible to discuss each in isolation without mentioning the others. On the other hand, it has seemed best to organize a discussion of the scientific problems of this essentially indivisible subject by using these aspects as headings. This interrelated set of phenomena like the following could conceivably be discussed under all these headings.

The rate of absorption of solar UV radiation and the consequent conversion of radiant energy to ionization or excitation energy or heat (energetics) depends sensitively on the composition, including minor constituents. The rates of the chemical reactions by which the constituents then release energy (chemistry) are dependent on the composition and temperature as is the rate of reradiation (energetics). But the local temperature is not exclusively dependent on these processes, because other sources of energy are involved, e.g., transport of heat from high latitudes or by dissipation of waves from below (energetics and motions). Furthermore, some constituents involving absorption, emission, and reactions have lifetimes long compared with times typical of large-scale motions, so local composition is modified, which modifies the energetics, which modifies the temperature, which modifies the chemistry, and so on.

The daytime steady-state ionosphere is established in the thermosphere principally by photochemical reaction of the dominant atmospheric constituents, oxygen and nitrogen. At midlatitudes under quiet solar conditions the behavior of the ionosphere can be reasonably well predicted, subject only to

uncertainties in the solar UV and EUV spectra and (to a lesser extent) uncertainty in the concentrations of the neutral species in the region. The effects of large variations in the solar electromagnetic flux (as during solar flares) are reasonably well understood.

The other principal sources of day-to-day variations in the thermosphere and ionosphere appear to be fluctuations in the energy flux of solar-wind particles arriving at the earth's magnetosphere and the interplanetary magnetic field, the efficiency of which in transferring energy to the magnetosphere is apparently governed by the relative orientation of the two fields. Most of the energy extracted by the earth's magnetosphere from the solar wind is deposited at high latitudes in the auroral zone. While the total energy input from this source is usually less than the solar UV and EUV flux deposited globally in the atmosphere, the fact that this energy input is concentrated within a narrow interval of latitude means that it can profoundly affect the global circulation of the neutral atmosphere (Figure 5.9).

The solar energy transmitted through the interplanetary medium produces three separate but related effects on the thermosphere and middle atmosphere. Heat is produced by direct electron and proton impact on the atmosphere during auroral and solar-flare events. Frictional (Joule) heating is produced in the atmosphere by electric currents flowing in the lower thermosphere (auroral electrojet). Momentum is transmitted to the neutral atmosphere by fast-moving ions in the upper regions (≥ 150 km) of the ionosphere.

The heat and momentum transferred by these processes to the neutral atmosphere in the thermosphere appear to be redistributed globally over the earth by winds and waves. The winds in the thermosphere preferentially transport the lighter atomic constituents of the atmosphere and can thus modify the global chemical composition. The overall heating of the thermosphere during geomagnetic storms can be a significant fraction (50 percent) of the global mean.

The electric field produced across the entire magnetosphere by the flowing solar wind is observed at thermospheric heights in the polar caps. Changes in this electric field, produced by changes in the solar-wind flow, can produce rapid motion of the ionized matter, with speeds of more than 1 km/sec at times. Changes in this magnetospheric electric field also appear to penetrate to lower latitudes, where they are comparable in magnitude with the fields produced by the atmospheric dynamo.

These two superimposed electric fields, both of which are highly variable because their origins are variable, are mapped downward and superimposed on the electric fields established by global thunderstorm activity. The possible interaction of these different electric-field generators in the global atmospheric electric circuit has been suggested as one means by which solar activity might affect the earth's weather.

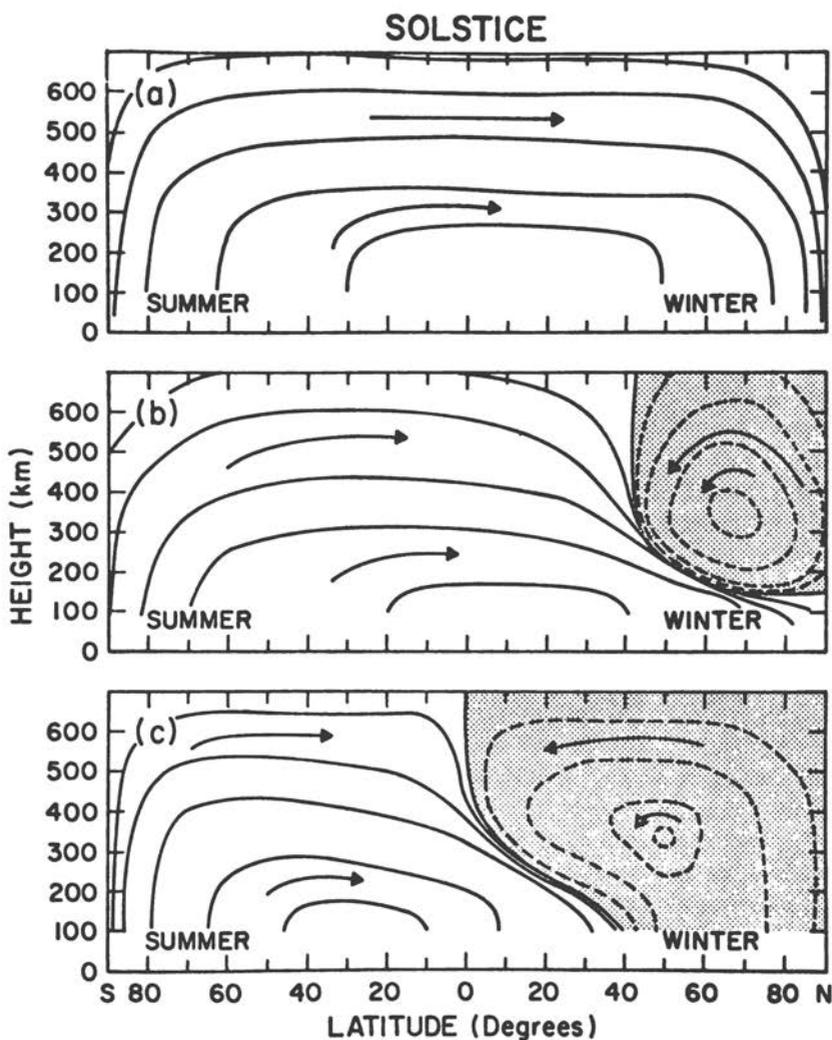


FIGURE 5.9 Diagrams of the mean meridional circulation in the thermosphere at the time of the winter solstice in the northern hemisphere, for three levels of auroral or geomagnetic activity. (Courtesy of R. G. Roble, NCAR.)

3. The Middle Atmosphere

The chemical processes occurring in the middle atmosphere and lower thermosphere are very complex; not all are even well recognized yet. Photodissociation of the normal oxygen molecule (O_2) produces odd oxygen—atomic oxygen O , ozone O_3 , and excited atomic oxygen $O(^1D)$. The ozone is distributed

in the atmosphere between the surface and about 100 km, with a peak concentration near 20 km, and serves as the most important absorber of solar UV in the atmosphere. Any major change in the amount of ozone in the atmosphere would have profound effects on many existing biological species.

The ozone abundance produced by solar photodissociation is largely determined by chemical radicals such as NO, NO₂, OH, HO₂, Cl, and ClO produced from chemical species that are to a large degree transported upward from the troposphere (below about 10 km). The constituents from which these radicals are produced by photochemical reactions include N₂O, CH₄ (methane), CFM's (chlorofluoromethanes such as CCl₂F₂ and CCl₃F), CH₃Cl, other halocarbons (including bromine compounds), and water vapor. All of these constituents are relatively stable molecules that are introduced into the troposphere and that gradually enter the stratosphere where they act as sources of radicals. The interactions among these reactive chemical species may be slowly changing as man continues to add CO₂, CFM's, and N₂O to the atmosphere in steadily increasing quantities.

The presence of radicals in the stratosphere leads to the formation there of several reactive chemicals such as HNO₃, ClONO₂, HOCl, and HO₂NO₂, by analogy with the same chemical reactions observed in the laboratory. Nevertheless, several of these chemical species, expected in concentrations of only 1 ppb or less, have not yet been detected in the stratosphere itself. Atmospheric constituents that are important in the formation of aerosols include SO₂, COS, NH₃, and H₂SO₄. Such carbon compounds as CO and various hydrocarbons such as H₂CO are also of importance for middle-atmospheric chemistry. Concentrations of these constituents must be known in order to understand the radiative energy balance that establishes the basic thermal structure of the atmospheric region. There is a complicated feedback in these processes since the absorption of solar energy is related to the chemical composition, but the heating itself affects the temperature-dependent chemical reaction rates, which in turn affect the chemical composition.

4. Scientific Problems

(a) *Composition and Chemistry*

(i) *Stratosphere* The chemistry of the stratosphere is exceedingly complicated, and the description of atmospheric composition must be very detailed in order to permit a realistic consideration of the chemistry (Figure 5.10). Whole families of substances of interest are present in the stratosphere in addition to the normal background of clean dry air. "Dry" is, of course, a relative term, and enough water vapor is always present to affect the chemistry in important ways.

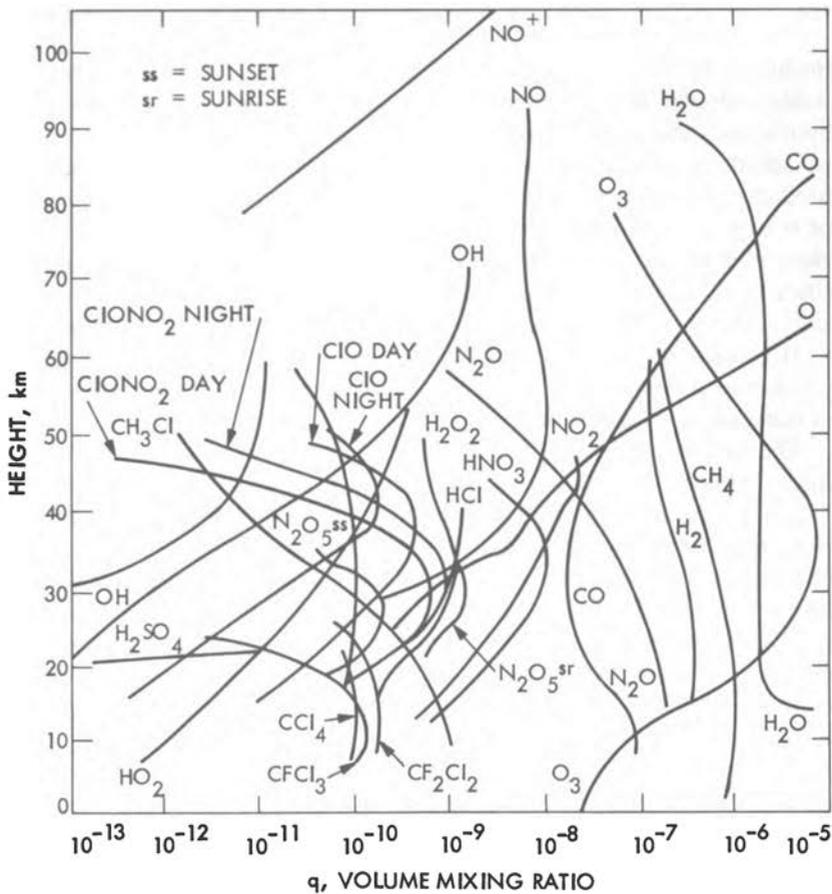


FIGURE 5.10 Altitude profiles of the concentration of minor constituent species in the middle atmosphere. (From the Report of the Science Definition Working Group, Upper Atmosphere Research Satellite, courtesy of the Jet Propulsion Laboratory, California Institute of Technology.)

Among the substances of interest (already noted above), probably the first that should be mentioned is odd oxygen—atomic oxygen O , ozone O_3 , and excited atomic oxygen O^1D —which arises from the photodissociation of O_2 by solar UV radiation with wavelengths shorter than 242 nm. Next are the radicals NO , NO_2 , HO_2 , HO , Cl , and ClO . These constituents, plus a few other chemical forms, are at times referred to as the “odd N,” “odd H,” and “odd Cl” families, because within each family the constituents are transformed relatively rapidly from one to another. The precursors of radicals—the constituents from which radicals arise through photochemical reactions—include N_2O , CH_4 , CFM’s (chlorofluoromethanes), CH_3Cl , other halocarbons

(including bromine compounds), and water vapor. These are the relatively stable molecules that are introduced into the troposphere either naturally or by man and that gradually enter the stratosphere, where they act as sources of radicals. Another category of interest comprises the radical-radical reaction products; these are generally inactive as catalysts, but they constitute a form of storage from which radicals can be released photochemically, and they include such species as HCl, HNO₃, ClONO₂, H₂O₂, HO₂NO₂, and HOCl. Constituents that are important in the formation of aerosols include SO₂, NH₃, and H₂SO₄.

Molecules such as COS (carbonyl sulfide) are inactive in the troposphere but can be photolyzed in the middle stratosphere to release S atoms, which in turn can be oxidized to form sulfuric acid aerosol.

The carbon compounds CO and H₂CO are also of importance to stratospheric chemistry. This provides an impressive array of constituents whose concentrations must be known, along with their distribution in altitude, latitude, and time just to describe adequately the compositional structure of the stratosphere. The concentrations of all of these constituents are small (typically a few parts per billion or less), and sophisticated techniques are needed to observe and measure them. Without measurements of most or all of these chemical species in the stratosphere itself, there must remain substantial uncertainty in our understanding of stratospheric chemistry, both on the average and in response to solar variations.

The various processes of interest are also numerous and in many cases difficult to observe. These include the generation of gases—the radical precursors—by biological or physical processes at the earth's surface, the removal of gases and particles from the troposphere (i.e., tropospheric sinks), the photochemical reactions in the stratosphere (and in some cases the troposphere), aerosol formation, heterogeneous reactions that take place on the surfaces of aerosols, radiative effects of gaseous constituents and aerosols, and atmospheric transport. In an oversimplified view of the problem, source molecules generated at the earth's surface mix rather rapidly through the troposphere and are slowly transported into the stratosphere, where they are converted into chemically active species—radicals—by photochemical reactions. However, some of the source molecules may be removed by sinks in the troposphere, reducing the number that eventually reach the stratosphere. Full understanding of the atmospheric cycle of each gas includes knowledge of its surface release rate, its loss to tropospheric sinks, its transfer to the stratosphere, and its loss to stratospheric sinks.

Many radicals that are released in the stratosphere participate repeatedly in catalytic reactions, but some of them become converted into inactive forms—those radical-radical reactions products that provide a form of storage. There is a steady slow transport of both the radicals and the inactive forms back

into the troposphere, where they are generally removed from the atmosphere by rain. In this way a relatively steady state is set up, but many complications arise as a result of alternate paths that some of the constituents may follow. Furthermore, the chemical problem is complicated by the nature of atmospheric motions; for example, where substantial vertical motions are associated with wave motions, the chemical reactions may take place preferentially in regions of higher or lower atmospheric density than that at the level under consideration.

Atmospheric aerosols is a general term that has been applied to matter suspended in the atmosphere ranging in size from 1 nm (molecular clusters) to micrometer-size particulates. Those with radii greater than about 0.1 μm act as particulates in scattering light, while smaller particles scatter light in the same way that molecules do. A considerable amount of research has been done on the larger aerosols over the last five years. The stratosphere has been found to be a rather stable reservoir for such particles. Since sedimentation is very slow, such particles remain in the stratosphere for relatively long times; typical lifetimes are of the order of a year in contrast to lifetimes measured in days in the troposphere.

It is now believed that aerosols are formed in the stratosphere by gas-to-particle conversion processes and that the major constituent is sulfuric acid, H_2SO_4 . The processes result in the formation of a layer of stratospheric sulfate particles at about 20 km. Typical stratospheric concentrations of these particles range from 0.5 to 10 cm^{-3} . The gaseous sulfur compound responsible for the formation of sulfuric acid droplets is thought to be mainly sulfur dioxide, SO_2 . Carbonyl sulfide, COS, known to be a by-product of coal combustion and possibly formed by other processes as well, has now been measured in the 0.5 ppb range in the troposphere, and theoretically it should not react substantially until it has diffused some 30 km into the stratosphere, where it is converted to SO_2 by photolysis. Thus, COS may be an important man-made source of stratospheric aerosols.

(ii) *Mesosphere* By comparison with the regions above and below it, the mesosphere is usually described as characterized by relatively simple photochemistry. Atomic oxygen is produced by the photodissociation of molecular oxygen by solar UV radiation in the Schumann-Runge bands. Above 55 km, the atomic oxygen remains mainly in that form during the daytime, but there is a large diurnal variation as it converts to ozone at night. Below 55 km, the atomic oxygen formed by photodissociation of molecular oxygen mainly converts to ozone, even in the daytime. Recombination of O and O_3 to O_2 in this region of the atmosphere is believed to be accomplished chiefly by catalytic reaction chains involving H, OH, and HO_2 .

There are only a few observations of O_3 in the mesosphere, and these few

provide little reassurance that we understand or are able to predict the concentration of such active species. In the tropics at night, the observed concentrations between 40 and 55 km have been found to be 3 to 5 times larger than anticipated, and above 55 km the profile is not at all like that expected. Similarly, one measurement of NO at 70 km is about 20 times the expected amount.

One would like to measure the concentrations of O_3 , O, OH, HO_2 , NO_x , H_2O , CH_4 , and H_2 and the diurnal variations of these constituents. At present, the most suitable means of doing this seems to be use of instruments suspended from parachutes ejected from sounding rockets. Infrared spectroscopic instruments planned for flights using the Space Transportation System (STS) also promise to provide valuable information on the global distribution of certain minor neutral constituents in the upper stratosphere, mesosphere, and lower thermosphere.

(iii) *Thermosphere* There are still no direct measurements in the lower thermosphere of chemically active species. Atmosphere Explorer measurements did not extend below 150 km, and it does not appear feasible to make *in situ* measurements below this altitude from satellites. A fundamental question that affects the structure of the thermosphere in a dominant way is the atomic and molecular oxygen distributions from 80 to 150 km. Measurements of atomic oxygen have been made with mass spectrometers in rockets, but recombination of oxygen on the surfaces of the rocket and spectrometer gives rise to questions about the validity of the interpretation of measurements. Airglow measurements from above provide another means of obtaining the atomic oxygen profile, since recombinations give rise to green-line emissions that can be interpreted in terms of atomic oxygen concentrations. However, such observations from OGO-6 have not satisfactorily answered the question of the atomic oxygen distribution. Molecular oxygen may also have seasonal, diurnal, and latitudinal variations in the lower thermosphere. Measuring the absorption of solar radiation from rockets and satellites is one way to determine the O_2 distribution.

Another important question relates to hydrogen compounds in the lower thermosphere. Although CH_4 and H_2O provide the source molecules for atomic hydrogen, and the escape flux from the top of the atmosphere is in the form of atomic hydrogen, the role of other species, e.g., H_2 , in carrying the upward flux needs to be established. Thus profiles of CH_4 , H_2O , H_2 , and H in the lower thermosphere are needed.

In the lower thermosphere and in the mesosphere, problems relating to the D region of the ionosphere remain, namely, identifying and understanding the sources of ionization, the steps leading to the formation of the dominant ions (and even the identification of the dominant ions in the case of negative ions),

and the mechanisms leading to ion removal. The ionization may be intimately linked with the NO distribution in the lower thermosphere and mesosphere, which is governed by solar and auroral causes. The highly variable auroral component can be transported globally by wind systems, and vertical transport to lower altitudes may perturb the ion and neutral chemistry of the mesosphere. Measurements made from sounding rockets, parachutes, and balloons are still required in order to provide such information.

The role of metals and ions in the lower thermosphere also needs further investigation. Somewhat higher up in the thermosphere, Atmosphere Explorer has demonstrated the importance of metastable neutral and ion species in controlling the chemistry; however, the global impact is still not understood.

The upper atmosphere is strongly perturbed at certain times and in certain places by auroral precipitation, solar proton events, and planetary waves. Measurements of the energy input, the changes in neutral and ion composition, and the radiative balance remain a requirement. Measurements made from sounding rockets and satellite remote sensing in certain airglow bands and atmospheric emissions, assisted by ground-based optical observations and incoherent-scatter radar, appear to be the most suitable methods for attacking this class of problems. Global imaging is necessary to provide time-dependent information for models.

(iv) Exosphere The current belief is that escape of hydrogen from the exosphere is dominated by nonthermal escape, principally charge-exchange collisions between energetic hydrogen ions and hydrogen or oxygen atoms. However, there has been no direct observational confirmation of this concept. Ground-based observations with new high-sensitivity optical instrumentation may provide some of the necessary information.

(b) Energetics

(i) Middle Atmosphere The term middle atmosphere is used here as encompassing the stratosphere and mesosphere. In the decade of the 1980's we can expect substantial progress in the formulation and solution of three-dimensional time-dependent models of atmospheric dynamics and electrodynamics through the middle atmosphere. The success of these models will depend in part on the availability of data on the energy budget of the system, i.e., the energy input at various altitudes, radiative energy transfer, chemical storage of energy, and energy transport by dynamical processes.

Satellites provide optimal platforms from which to make global measurements of energy input in to the middle atmosphere. To evaluate the effects of man-made or natural perturbations on the composition of the middle

atmosphere, more detailed information is needed on quantities associated with the interaction of UV, visible, and infrared radiation with the gaseous constituents and atmospheric aerosols. It is clear that satellite observations must be supplemented and complemented by balloon, aircraft, and ground-based measurements. The quantities to be measured include the spectral distributions of the solar and terrestrial radiation fields as functions of altitude, location, and season; the albedo of the underlying combined surface-plus-atmosphere system; and the spatial distribution of radiatively active constituents such as O_3 , H_2O , and CO_2 and/or aerosol particles.

Of the many problems and unknowns in the middle-atmosphere radiation budget, we highlight one that presents a large uncertainty in calculating rates of atmospheric heating. Our present knowledge of the optical properties of stratospheric aerosol particles leads to about an order-of-magnitude uncertainty in deriving stratospheric heating rates caused by the particles, and uncertainty even in sign appears in evaluating the effect of particulates on global-average surface temperatures.

Aerosol particles are known to be located in the stratosphere in the interval at about 15–25 km with highly variable concentrations, especially following major volcanic eruptions. High concentrations of particles have also been found in other regions of the upper atmosphere, as attested to by the presence of noctilucent clouds at the mesopause and by occasional reports of aerosol layers at intermediate levels. Significant effects on the energy budget of the atmosphere were associated with the increase in aerosol concentrations observed after the eruption of the volcano Mt. Agung in early 1963. Approximately a year after the eruption, for example, temperature increases of 6 to 8 K were observed near the 20-km altitude level throughout the equatorial region.

A significant uncertainty also exists in our ability to specify the vertical distribution of the direct and diffuse UV radiation field. This is important not only for use in calculating the amount of energy absorbed by atmospheric constituents but also for use in photochemical calculations. Data on the spectral distribution of solar radiation outside of the atmosphere are available from solar sensors on orbiting satellite platforms. However, the changes in the direct and diffuse solar UV radiation as it propagates downward are usually specified by using empirical values in the models. The calculation schemes must be tested. *In situ* observations using instrumentation mounted on balloons and rockets to determine the direct and diffuse UV radiation fields are required for the validation and improvement of the stratospheric models.

Energetic particles provide both a quasi-steady and a sporadic energy input to the upper atmosphere at high latitudes. Fluxes of energetic protons follow major solar flares, and the bulk of their energy is dissipated in the form of

ionization, mainly in the mesosphere in the case of protons with energies less than about 30 MeV and in the stratosphere in the case of higher energies. The total energy input during a solar-proton event can be significant in comparison with other upper-atmospheric energy sources.

In the middle atmosphere the ionization process is accompanied by dissociation of nitrogen and water vapor, leading to the formation of a wide range of odd-nitrogen and odd-hydrogen compounds that can initiate catalytic chemical-reaction chains. The energy released by the catalytic reactions can far exceed the initial energy input from the particles themselves, since the catalytic chains effectively tap the storehouse of chemical energy in the upper atmosphere. The largest single component of stored chemical energy in the middle atmosphere is dissociated oxygen in the form of atomic oxygen and ozone. The catalytic action of NO_x and HO_x compounds has the effect of increasing the rate at which recombination of O_3 and O proceeds. The HO_x chain is most effective in the mesosphere, but it has a relatively short duration since the lifetime of HO_x is only of the order of a day at these altitudes. The NO_x chain is most effective in the stratosphere, and it may have a long-enduring effect because of the relatively long photochemical lifetime of NO_x .

An exciting prospect for the 1980's, namely, the possibility of gaining a better understanding of global electrodynamics, was discussed from the standpoint of magnetospheric and ionospheric physics and is recapitulated here because of its potential importance to atmospheric physics as well. Electric fields are present at all heights of the atmosphere and have a significant impact on the energy budget in the thermosphere. High-altitude electric fields have been shown to penetrate to stratospheric levels where they perturb the global atmospheric electric potential distribution. On the other hand, electric fields associated with thunderstorms perturb ionospheric fields and currents. This upward and downward mapping of electric fields is one of the few clear, almost instantaneous, coupling mechanisms between upper and lower atmospheric processes. To make progress, we need to explore the interactive effects of thermospheric, mesospheric, and stratospheric electric fields and the possible coupling of high-latitude electric fields to middle- and low-latitude regions on a global scale and for extended time intervals.

(ii) *Thermosphere* Ultraviolet radiation from the sun provides an important and relatively steady heat input into the thermosphere. This input varies with the solar cycle and produces a solar-cycle variation in exospheric temperature. Shorter-term variations result from enhanced radiation associated with solar flares. An average energy input due to the absorption of solar UV radiation in the thermosphere is about 10^{12} W above 100 km.

Heat input into the upper atmosphere from the magnetosphere constitutes

another important heat source. It includes quasi-steady components due to Joule heating by electric currents and particle precipitation around the auroral oval that is present nearly all of the time; this has been estimated at about 5×10^{10} W for average conditions of auroral activity. During magnetic storms, the Joule heating and particle-precipitation energy-input rate can be an order of magnitude greater (5×10^{11} W). During strong geomagnetic storms about an order of magnitude more energy than is deposited in the auroral zones goes into the injection of energetic particles that become trapped in the earth's magnetic field to produce a ring current; this energy decays at a rate roughly a factor of 10 times slower than the rate of injection. Some of this ring-current energy (perhaps 10 percent) is directly deposited in the middle- and low-latitude regions of the upper atmosphere (i.e., at a rate of about 5×10^{10} W) as the ring current decays. Particle energy from the magnetosphere can be directly deposited by ion and electronic precipitation, flow of Joule heat from the ring current, and energetic neutral-particle precipitation. These quantities are poorly known. There is a need for coordinated measurements of optical emissions, ionization production rates, electric fields, and electron- and ion-temperature gradients along the field lines to evaluate the auroral-zone energy inputs and their variation in local time, and energy transport to lower latitudes, as well as the direct energy inputs to middle and low latitudes.

Precipitation of trapped energetic particles into the atmospheric loss cone induced by ULF-VLF waves constitutes an energy source for the thermosphere and mesosphere. Both coherent and incoherent wave forms are present in the magnetosphere, and they may precipitate particle fluxes that have energies orders of magnitudes larger than the energy fluxes in the scattering waves. A variety of wave-induced effects occur both in and outside the plasmasphere. These effects have not yet been well described in terms of the types of scattering waves, the particle energies involved, and the temporal and spatial characteristics. The problem is further complicated by the presence in the magnetosphere of VLF waves from communication and navigation transmitters and from power distribution systems.

In the 1980's, satellites and Shuttle-based techniques can play an important role in describing the particle inputs to the atmosphere associated with scattering by waves, particularly the quasi-steady effects. However, the important dynamical effects such as fast temporal variations will require observations of precipitation effects (and associated wave activity) from the ground and from balloon and rocket platforms. The appropriate instruments include photometers, x-ray detectors, riometers, magnetometers, and ULF-VLF receivers. Each of these techniques is currently undergoing improvements. These improvements should be continued so as to provide the instrumental basis for mapping precipitation, supporting associated space experiments, sup-

porting active wave-injection experiments, and evaluating man-made precipitation effects.

(c) *Structure and Motions*

(i) *Middle Atmosphere* The principal energy sources of the lower and middle atmosphere are, respectively, solar heating of the earth's surface and of the ozone layer. This leads to a structure where the temperature decreases with altitude through the troposphere, increases through the stratosphere to a maximum near 50 km, and again decreases through the mesosphere. The latitudinal differential in the heating of the ozone layer by absorption of solar UV energy, and the subsequent infrared emission to space from ozone, carbon dioxide, and water vapor, drives a global circulation that is characterized by a strong west to east jet in winter and a strong east to west jet in summer, centered at altitudes near 60 km. Thus, there is a strong annual periodicity in the middle-atmosphere flow. Other notable periodicities in the flow include the quasi-biennial oscillation that is prominent in the lower stratosphere near the equator and the semiannual oscillation that dominates at higher levels in the tropics. The source of the quasi-biennial oscillation is believed to be the alternate eastward and westward acceleration arising from vertically propagating tropical wave modes. The source of the semiannual oscillation is more uncertain but is thought to lie in alternate eastward and westward accelerations arising from vertically propagating tropical wave modes and extratropical planetary-scale disturbances that have their sources in the winter troposphere. At middle and high latitudes, somewhat irregular oscillations with one- to three-week periods are seen in the winter flow; these are commonly referred to as minor warmings. Also, there is the sudden stratospheric warming—a high-latitude phenomenon that appears during some winters.

These middle- and high-latitude phenomena are thought to be intimately connected with vertically propagating planetary waves that are evident on winter weather maps as large-scale undulations in the flow. The vertical motions that accompany these global flows are small, on the order of 1 cm sec^{-1} or less. Synoptic-scale disturbances (those flows that are familiarly seen as migrating highs and lows on weather maps) are believed to play a much reduced role in the middle atmosphere compared with their role in the troposphere. However, observations are inadequate to settle this issue at present.

Atmospheric tides are global-scale motions that are driven by the sun and the moon by their thermal and gravitational influences; they have periods equal to integral fractions of a solar or lunar day. Tidal winds are observed to be comparable with prevailing winds in the upper mesosphere and lower thermosphere. Gravity waves are much shorter-period oscillations that are forced by auroral disturbances, severe weather, and shear instabilities, as

well as by other means. The vertical propagation of gravity waves upward from the troposphere is thought to act as an appreciable energy and momentum source for the middle atmosphere and above.

Turbulence arises in the atmosphere from instability in the large-scale flow, as well as instability of tidal and gravity waves. The role, and indeed the source of turbulence above the lower stratosphere, is quite uncertain at this time, although there does appear to be evidence for an appreciable enhancement in mechanical dissipation above the stratopause due to the breaking of tidal and gravity waves there.

A great number of constituents of the upper atmosphere have chemical time scales that are much greater than the time scales for transport. Examples are O_3 in the lower stratosphere and NO in the mesosphere. For these and other constituents, consideration of transport must be included in efforts to understand the chemistry. Although transport of chemical constituents takes place in response to motions on a variety of time and length scales, global distributions of species are thought to be primarily the results of chemical processes and planetary-scale motions with periods of several days and longer. Smaller-scale motions are important in several contexts, however. Perhaps the most important of these is the stratosphere-troposphere exchange of air that is thought to occur in processes associated with the upper-tropospheric jet stream.

Transport of heat and the adiabatic heating and cooling that accompany vertical motions also play a significant role in determining the temperature structure of the middle atmosphere. Observations from satellite platforms can provide the global coverage necessary for the study of large-scale phenomena. Aircraft measurements are appropriate for somewhat smaller-scale phenomena. Long-duration balloons act as tracers. Ground-based measurements that give continuous measurements are suitable for the study of wave structures and turbulence. To study the full range of dynamics, a proper combination of all of these measurement techniques is required.

(ii) Thermosphere and Ionosphere The circulation and temperature structure of the low- and middle-latitude thermosphere are primarily controlled by heating due to the absorption of solar extreme ultraviolet (EUV) and UV radiation. Yet the structure established by solar radiant heating is frequently perturbed by thermospheric waves and changes in the mean circulation that are generated by auroral substorms and geomagnetic activity that propagate equatorward through the region. These perturbations are manifestations of the global redistribution of auroral energy that is deposited locally in the high-latitude thermosphere. Thermospheric dynamics is strongly governed by the magnitude of the high-latitude heating because the variations in this heating are so large (three orders of magnitude).

Two processes appear to be important: namely, electric current flowing at

altitudes of 100 to 140 km and the precipitation of energetic particles. While the presence of currents can be detected from ground-based measurements of magnetic-field perturbations, the heating rate is best determined by direct observations of the ionospheric electric fields that drive them, together with measurements of the conductivity of the region in which they flow. These can be made only by means of ground-based incoherent-scatter radar.

With regard to the energy input by particles, substantial knowledge of the spatial and temporal variation of auroral precipitation has been gained from ground-based optical and spacecraft observations. Local heating rates from these auroral processes can be much larger than solar EUV heating, with consequent major influence on the dynamics and composition of the thermosphere. A more widespread particle energy input occurs in connection with rare solar-proton events that engulf the polar cap and auroral zone.

As a consequence of the irregular way in which auroral heating occurs, the thermosphere is dynamically active and is in a constant state of imbalance. Since the effective energy transport is meridional in the thermosphere, the existing incoherent-scatter radars (Millstone Hill, Arecibo, and Jicamarca) that lie along the 70° W meridian can be used to study the equatorward progression of thermospheric waves and circulation perturbations that are launched at high latitudes. The data obtained by these and optical stations can be analyzed with the help of numerical models of thermospheric circulation and temperature structure. These studies will define the dynamic processes that are so important in the global redistribution of auroral energy throughout the entire upper atmosphere.

The influence of electrodynamic phenomena is more complex. As noted above, substantial electric fields are present in the thermosphere. The total energy input from these fields in the auroral zone and polar cap is comparable with that from solar EUV radiation and auroral precipitation. A particular concentration of such energy release occurs within the "throat" region of the magnetospheric polar cleft or cusp, where very large electric fields are continually present. There is currently no way of obtaining direct information about the behavior of the cusp or polar-cap electric fields, currents, or energy dissipation on a day-to-day basis.

A second influence exerted through high-latitude electrical processes is the transfer of momentum from the ionospheric plasma to the thermosphere. Models of thermospheric dynamics indicate that this momentum source is of key importance for understanding the global behavior of the thermosphere during periods of magnetospheric disturbance. An incoherent-scatter radar located in a position to observe the cusp in the local-noon sector and monitor the polar cap at all local times would be a powerful tool for making progress on this problem. Serious consideration should be given to placing a high-latitude station in such a position to extend the meridional chain of existing stations to study global thermospheric response to auroral energy inputs.

The lower thermosphere (90-150 km) is a region affected by thermospheric processes from above and by tidal, planetary, and gravity waves from below. Since many species produced in this region like NO and O are long-lived, they are affected by transport processes as well as by fast nonlinear chemistry. To understand this region it is necessary to determine the mean circulation and temperature structure as well as the response to changes in the tidal structure and changes produced by geomagnetic activity. That is, dynamics has an important role in determining the compositional structure, which in turn affects processes in the thermosphere above and the mesosphere below. Observations of tides by incoherent-scatter and meteor-wind radars have shown that these are variable in both time (from day to day) and location (over distances of 1000 km), apparently reflecting the effects of background winds in the mesosphere in coupling energy from the fundamental into higher-order modes. This greatly complicates the dynamics of the lower thermosphere and has made it difficult to establish the average tidal behavior. A concerted effort is needed during the next few years to achieve this.

Numerical models of the global distribution of temperature, density, and composition are extremely useful for a number of upper-atmospheric studies, since they conveniently summarize the large-scale structure of the thermosphere. The growing collection of observed quantities should be used to periodically update models and improve their performance. The pressure forces specified by these semi-empirical global models of neutral temperature and composition can be compared with those deduced from measurements of winds by incoherent-scatter radar, optical means, and possibly satellite techniques. These studies provide a consistent check on the longitudinal and latitudinal gradients of neutral temperature and composition in the semi-empirical models, since these variations primarily govern the thermospheric wind structure. Particular emphasis should be placed on improving the time-dependent predictive capabilities of the models by including the effects of tides propagating into the lower thermosphere and the response to auroral heating.

Planetary and gravity waves launched by weather fronts and other sources in the troposphere or stratosphere appear capable of propagating into the thermosphere, where they dissipate their energy through the action of viscosity. The importance of these phenomena for creating motions in the thermosphere that give rise to significant heating and/or transport effects remains uncertain and must be explored. It remains to be seen whether they can then be incorporated in the models outlined above.

The dynamics of the ionospheric plasma constitute a separate scientific study, but related to that of the neutral atmosphere. At thermospheric heights electrons are set in motion only by electric fields. At midlatitudes these are generated by tidal winds that transport ions across magnetic field

lines and establish polarization electric fields, while at high latitudes electric fields are impressed into the ionosphere by the interaction of the solar wind with the earth's magnetosphere. Ions can be transported horizontally by winds at altitudes below about 130 km, but at greater heights winds drive them only in the magnetic-field direction. Above about 150 km, electric fields drive ions across field lines in the same direction as the electrons. These ion motions serve as tracers of winds and electric fields for the incoherent-scatter radar technique.

In the presence of strong density gradients combined with electric fields, ionospheric plasma can become unstable in the sense that small density perturbations grow, creating large density fluctuations. Irregularities resulting from several processes appear to exist, and under appropriate conditions they can combine to create large irregularities in the plasma density with scales of kilometers down to centimeters. It is possible to stimulate these irregularities artificially by such means as using a large high-frequency transmitter to deposit energy in the ionosphere. Research on these phenomena contributes to the understanding of plasma processes in a way that is often difficult to achieve in the laboratory.

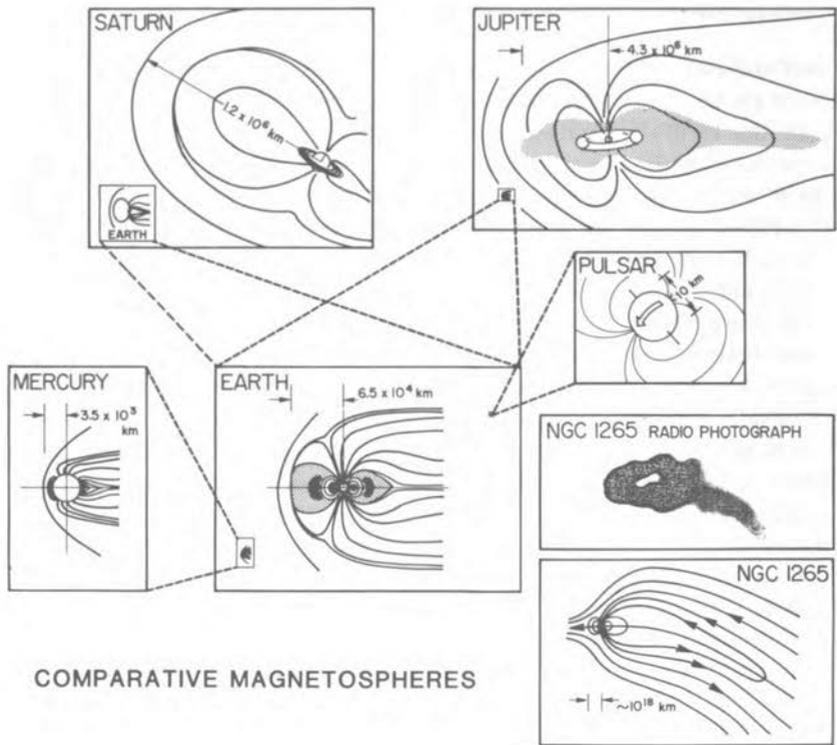
VI. COMPARATIVE STUDIES OF THE PLANETS AND THE SOLAR-TERRESTRIAL SYSTEM

1. Introduction

The earth is only one of the planets in the solar system. Thus it can be said that research in solar-terrestrial physics is a special case of research in solar-planetary relations. Comparative studies of such features of the planets as their magnetospheres, ionospheres, and atmospheres are a stimulating experience and lead toward an understanding of the solar system as a complete entity. The consequence is that fresh insights into solar-terrestrial relations can be provided by understanding the wide range of interactions displayed by the other solar-planetary systems. We describe below two areas that are of importance to solar-terrestrial physics—the magnetospheres-ionospheres of the planets and comets and the atmospheres of the planets.

2. The Magnetospheres-Ionospheres of the Planets and Comets

There are several planets that are known to have strong enough intrinsic magnetic fields to stand off the solar wind and create magnetospheres above their ionospheres. These are Mercury, earth, Jupiter, Saturn, and perhaps Mars (Figure 5.11).



COMPARATIVE MAGNETOSPHERES

FIGURE 5.11 Comparative magnetospheres. Fundamental similarities characterize the magnetospheric configurations of the planets in the solar system and some other celestial objects in the universe at large, but their scales are vastly different because of differences in their intrinsic magnetic fields and associated plasmas. Among the planets, Mercury's magnetosphere is tiny compared with the earth's, while Jupiter's is enormous—an order of magnitude larger than the sun itself. The size of the magnetosphere of a typical pulsar is of the same order of magnitude as the earth's, but its magnetic field is trillions of times as strong. Plasma is locked into its magnetic field until it is spun up to nearly the speed of light. As the radio galaxy NGC 1265 (shown here with a map of radio emission for comparison) plows through the intergalactic gas, the ram pressure creates a magnetospheric tail stretching millions of light-years into space. The distance of 10^{18} or a million trillion kilometers shown by the marks is the equivalent of a hundred thousand light years. (Courtesy of NRL, based on earlier figures by the NASA Goddard Space Flight Center and L. J. Lanzerotti.) See also Figure 5.2, the heliosphere, which is the magnetosphere of the sun.

In the case of Mercury, a bow shock is created in the solar wind about 1.4 planetary radii from the subsolar point. The magnetosphere of Mercury is similar to that of earth with the important difference that the solid planet occupies a large fraction of the total volume of its magnetosphere. Further-

more, there is no proper atmosphere on Mercury, so that the magnetosphere contains no energetic particle belts in the region of the undistorted planetary magnetic field.

The magnetic field of Mars is so weak that the solar wind may interact directly with the atmosphere at times. Unfortunately, despite the many probes that have been sent to Mars, only the U.S. spacecraft Mariner 4 carried instruments designed to study the solar-wind-magnetic-field interaction.

The magnetosphere of Jupiter has been the subject of fairly intensive exploration already and is scheduled to receive even more attention. It is stretched into a shape possibly unlike that of the earth's, is modulated at the Jovian 10-h rotation period, and displays rapid changes in configuration and shape, on a scale of minutes. In contrast with the earth's magnetosphere to which charged particles are supplied mainly by the solar wind, the source of trapped particles in the Jovian magnetosphere is the ionosphere of Jupiter itself and the torus of heavy ions and electrons that surrounds Jupiter near the orbit of Io. Electrons in the energy range of tens of MeV escape from the magnetosphere and constitute the major source of such particles in the solar system.

Pioneer 11 and more recently Voyagers 1 and 2 detected a magnetosphere at Saturn and found it to be more like the magnetosphere of the earth than Jupiter's. It has its own interesting singularity in that it is strongly perturbed by the sweeping action of Saturn's rings on the trapped particles.

The Pioneer Venus mission has demonstrated that Venus, in contrast with the other planets, has little if any intrinsic magnetic field. The consequence is a strong direct interaction between the solar wind and the ionosphere and atmosphere. The magnetic interaction is with the induced field created by currents flowing in the ionosphere. The solar wind also interacts with comets, which probably accounts for the long ion cometary tails that develop when comets approach the sun.

Study of this rich variety of solar wind-planetary interactions provides a useful background for our efforts to understand the magnetosphere of our parent planet—earth.

3. The Atmospheres of the Planets

The atmospheres of the planets offer us a wide range of masses, rotational forces, topographical effects, atmospheric constituents, thermal time constants, and solar heating. Thus we are presented with a wide range of mixtures in the forces and processes that control atmospheric circulation and temperatures. The effects of individual processes can be isolated on some planets, so that the contribution of similar processes to terrestrial weather and climate can be evaluated.

Until the results obtained by the Pioneer Venus missions and Soviet

Veneras 11 and 12 can be fully digested, the atmosphere of Mars will remain the nonterrestrial atmosphere that has been most intensively studied. The size, surface temperature, length of day, and solar illumination are roughly comparable for the planets earth and Mars, although their interaction with the solar wind is different. On the other hand, the Martian atmosphere exerts a surface pressure that is only about 1 percent of that on earth, and it is composed almost entirely of CO_2 . The surface features on Mars are so large that they extend over an appreciable fraction of the atmospheric layer, i.e., their vertical extent is of the order of an atmospheric scale height. Consequently, the effect of topography on winds—so-called orographic forcing—appears to be important. Martian probes have in fact obtained evidence that this is the case. Mars offers an excellent laboratory for testing theories of orographic forcing and propagation of forced waves. More detailed studies than those now available are needed, however.

Large latitudinal and seasonal variations of temperature have been observed on Mars, while tides and gravity waves are prominent dynamical features in the atmosphere. Surface wind velocities as large as 60 m/sec have been observed. The atmosphere of Mars is extraordinarily dusty, and enormous dust storms systematically occur. The absorption of radiation by dust is important in determining atmospheric properties, as are processes involving the exchange of atmospheric CO_2 and H_2O with the polar caps. Yet, despite the results of the Viking mission there is not yet an adequate data base available to allow us to sort out the influence of latitudinal, longitudinal, seasonal, topographic, and dust-related effects on the Martian weather. Further study will be rewarding.

The atmosphere of Venus consists predominantly of CO_2 , with a surface temperature of 700 K and a pressure 90 times as large as that of earth. The Pioneer Venus mission was designed with the study of the atmosphere of Venus as its primary objective. Analysis of the data obtained is not yet complete but promises to provide us with a great advance in our understanding of the properties of this extraordinary atmosphere. Already we know that large-scale circulation is so important in transporting heat in this massive, ocean-like atmosphere that there is little difference in temperature between night and day, equator and pole. We know that deposition of energy in the cloud layers lying 40 to 70 km above the surface is important. Probably the most striking property of the atmosphere is the large zonal wind velocities that are attained even below the clouds, where pressures are greater than that at the earth's surface and wind velocities are greater than 100 m/sec. The amount of energy stored in the weather machine of Venus is enormous.

Jupiter has a massive atmosphere and a large rotational velocity. Understanding the extraordinarily stable zonal cloud and circulation patterns separated by regions of great turbulence as revealed by the Voyager images pre-

sents a great challenge to atmospheric scientists and the promise of rich rewards.

A most interesting discovery made by the Pioneer Venus and Voyager missions was evidence for lightning in the atmospheres of Venus and Jupiter. The existence of lightning in atmospheres that contain no clouds like the ice and water droplet clouds of earth is surprising and difficult to understand. In view of our incomplete understanding of processes leading to the generation of terrestrial lightning, these discoveries could conceivably lead to important advances in our understanding of this phenomenon.

Historically, our present conception of the genesis of planetary atmospheres was the consequence of the discovery by the Mariner 5 and Venera missions that the atmosphere of Venus contains approximately as much CO_2 as can be accounted for on earth in the inventory of CO_2 in carbonate rocks and buried sedimentary carbon. This discovery, along with discoveries in paleobiology, has stimulated dramatic advances in our understanding of the development of an oxidizing atmosphere and various life forms on earth.

Another achievement that resulted from the need to understand the stability of CO_2 in the atmospheres of Venus and Mars, despite the tendency of UV radiation from the sun to turn them into atmospheres consisting mainly of CO and O_2 , was the development of modeling techniques involving complex gas-phase chemistry and vertical transport of gases. Techniques were then available to understand the effect of man-made pollutants on the ozone layer in the stratosphere when the need arose in the early 1970's. Examples like these are illustrative of the benefits for solar-terrestrial research that can accrue from solar-planetary studies.

6

Societal Impacts

The creation of many of today's technologies—satellites, global communication and weather monitoring systems, and national defense activities—has come to rely on the knowledge gained from solar-terrestrial research. Solar-terrestrial research has contributed to our appreciation of the fragility of our environment and the increasing understanding of the effects of the variable sun on several aspects of this environment. The re-entry of Skylab excited widespread popular interest in an event that contained as ingredients such issues as our ability to predict solar activity on an operationally useful time scale and the response of the earth's upper atmosphere (and its consequent density increase) to the variable sun.

While some applications have been discussed briefly elsewhere, this chapter highlights by selected example the impact that solar-terrestrial research has made on society and technology and points out how the research objectives cited in other chapters are connected to several areas of present or potential application.

Described below, then, are the following four areas in which solar-terrestrial research is central to impacts on society and technology: (1) predictions of the space environment; (2) stratospheric ozone, a feedback loop between the biosphere and the solar-terrestrial system; (3) the evolution of ionospheric physics; and, last but certainly not least, (4) the sun-weather connection—a great enigma.

I. PREDICTIONS OF THE SPACE ENVIRONMENT

The United States has developed sophisticated operational space capabilities that are essential elements of national welfare and national defense. Thus, the

very capabilities—rocket and space technology—that fostered the rapid advance in solar-terrestrial research have evolved to become consumers as well as sources of knowledge. The development and operation of modern space systems—be they interplanetary research spacecraft, meteorological spacecraft, commercial communications satellites, manned Space Shuttles, or military missions—depend on an accumulated fund of knowledge in solar, atmospheric, and ionospheric research and understanding of the properties of magnetospheric radiations and plasmas as well as knowledge of the expected fluxes of solar and galactic cosmic rays. This fund of knowledge needs expanding and updating as the ever-increasing complexity of space systems highlights the need for information about new areas. The recent interest in the differential charging of spacecraft by space plasmas as well as in the effects of high-energy cosmic rays on microelectronics are examples of the use of established principles of physics in new applications.

The temporal variability of the space environment of interest typically spans the range from seconds to many years. Some systems, for example, manned spacecraft, have an urgent need to be immediately informed of the occurrence of potentially hazardous solar-proton events. Similarly, high-flying aircraft traversing the polar regions are also routinely alerted when solar-proton events are in progress. The spacecraft designer and operator, on the other hand, would like to see the properties of the environment, in which these creations must operate, predicted years in advance. Thus space environmental predictions over a wide range of time scales are of practical and necessary interest.

At present there is a growing interest in applying our improved knowledge and ability to forecast disturbances in space to the forecasting of the effects of such disturbances on ground-based systems. For example, it has been known for many years that geomagnetic storms cause difficulties in cable communications systems and can disrupt power-distribution systems. More recently it has been observed that geomagnetic activity can induce substantial electric currents in oil and gas pipelines, hastening corrosion and disturbing monitoring systems. Utilities and communication corporations are thus interested in the possibility that a forecast of magnetic-field variations on a regional basis might provide a technique for alerting the operators that unusual current flows may be expected. Conversely, exploration geophysicists could benefit from a forecast of geomagnetically quiet conditions in order to optimize the efficiency of airborne surveys and searches for ores and minerals carried out by means of sensitive magnetometers.

The anticipated increase in the utilization of space because of the availability of the Space Shuttle suggests that increasing demands will be placed on the national capabilities to forecast the behavior of the space environment. The increasing complexity of spacecraft and the very fact that people will be flying aboard the Shuttle with increasing frequency in the 1980's will bring

additional requirements for warnings and alerts. While, in many instances, it is possible to make space systems relatively immune to environmental effects through careful engineering design, such immunity is often purchased only at considerable cost. The cost tradeoffs depend on the presumed accurate knowledge of the space environment and the variability of the environment.

The development of advanced space systems—such as the Solar Power Satellite (SPS) program, which is currently under discussion—is already drawing on the intellectual resources and data base developed by solar-terrestrial research of the past. In this instance, such issues as the disturbance of the stratospheric and ionospheric chemistry by the large advanced launchers—far larger than the Shuttle—which would be required to boost an SPS into low earth orbit are of concern. The effects of ion engines (required to transfer SPS to synchronous orbit) on magnetospheric particle populations and energy flows, as well as the effects of the transmission of gigawatts of microwave power through the ionosphere to power converters on the ground, are also clearly problems that require detailed consideration. These problems span broad areas of solar-terrestrial research and address crucial questions of the effect of man on the relatively fragile environment of near-earth space. Such questions may well be typical of what future planners of advanced space systems will face; the scale of the problems will, of course, depend on the level of commitment that our society will make to the “industrialization” of space.

Central to such questions are fundamental problems in mesospheric and thermospheric chemistry and dynamics as well as in interplanetary-magnetosphere and magnetosphere-ionosphere coupling. The answers may be obtainable only by sound, well-structured research programs beginning with small-scale pilot projects. It seems almost inevitable that some of the issues will be resolved only by active experiments involving several specific disciplines of solar-terrestrial research.

II. STRATOSPHERIC OZONE: A FEEDBACK LOOP BETWEEN THE BIOSPHERE AND THE SOLAR-TERRESTRIAL SYSTEM

Perhaps the clearest example of a solar-terrestrial effect on man and his technology is provided by the ozone layer. Ozone is formed by the attachment of a free oxygen atom to an ordinary oxygen molecule, and the free oxygen atoms themselves are provided by photodissociation of molecular oxygen by ultraviolet (UV) sunlight in the 175- to 242-nm wavelength range. Despite its thinness (0.3 cm at atmospheric pressure) the ozone layer plays an essential role in the preservation of life on earth, since it absorbs nearly all of the potentially lethal solar UV radiation that enters the atmosphere. In par-

ticular, the so-called UV-B radiation, from 280- to 320-nm wavelength, is heavily absorbed and is thus prevented from irradiating surface-dwelling organisms. The sun's radiative output in this wavelength range is relatively high, and the absorption cross sections of DNA and protein are also large; thus it appears that the existence of an ozone layer must have been a necessary condition for the development of most of the life forms that we know today.

The sun controls the amount of ozone in the stratosphere directly, by providing the UV radiation necessary to create ozone, and, somewhat less directly, by influencing the ozone loss mechanisms. The sun's radiative output is remarkably constant at visible wavelengths, varying by at most a few tenths of a percent over a time period of decades. At extreme ultraviolet (EUV) and x-ray wavelengths, on the other hand, solar variability is pronounced on a wide range of time scales. The UV radiation responsible for producing ozone lies between these regions, but the sun's variability in the 175-242-nm wavelength range has not yet been studied adequately. There are, however, indications that significant variability does exist over the 11-year solar cycle, and calculations have shown that corresponding variations in stratospheric ozone should also occur. Some indications of such variation have been obtained from data taken with the Nimbus-4 satellite, but coverage did not extend over a complete solar cycle. In addition, the occasional large solar flares produce NO_x and HO_x in the mesosphere and upper stratosphere, and variations in ozone content are both calculated and observed in high-altitude, high-latitude regions of the atmosphere.

Solar-terrestrial effects also play a part in determining the effectiveness of the NO_x sink for stratospheric ozone, both directly through the generation and precipitation of energetic particles (which, in turn, create NO_x in the atmosphere) and somewhat less directly through the modulation of galactic cosmic-ray fluxes. The importance of these effects in terms of total ozone content, however, is difficult to assess quantitatively. The full consequences for society and technology of changes in the stratospheric ozone content are also difficult to assess. The chief areas in which the impact would be felt, however, can be briefly described as follows.

1. Direct Ultraviolet Radiation Effects

As mentioned above, the UV-B radiation that is filtered out by the ozone layer has a high cross section for destruction of DNA and protein, which are the chief building blocks of most life forms. Cells are thus quite vulnerable to increases in the intensity of UV-B radiation, such as would result from a decrease in ozone content. Fortunately for the biosphere, both plants and animals have developed highly effective defense mechanisms against such effects, including the development of such tanning pigments as melanin in man in

order to prevent penetration of the UV radiation, and of enzymatic repair mechanisms for radiation damage by both plants and animals. Many organisms exist, in fact, in a continual state of delicate balance between destruction and repair of cells, and any external effect that upsets this balance can have severely detrimental effects.

The effects of decreases in UV-B radiation, such as would result from an increase in stratospheric ozone, may not be negligible. In man, UV-B radiation does have a role in generating vitamin D, while in plants it is used to some extent in photosynthesis. Although global photosynthetic activity is probably limited more by the availability of nutrients or water than by photon fluxes, the latter may be important in certain environments.

2. Climatic Effects

Ozone has a dominating influence on the climate of the middle atmosphere, since the radiation that it absorbs is ultimately turned into heat and provides the driving force for stratospheric and mesospheric wind systems. Although the climate of the middle atmosphere has apparently little or no direct effect on the tropospheric climate, there may be an indirect effect through the fact that upward transmission and reflection properties for tropospheric planetary and gravity waves are determined by middle-atmosphere parameters. The potential influences of man's activities on stratospheric ozone are complicated still further by the possibility that preferential attack (e.g., by chlorine) might occur in the upper stratosphere with a resulting change in the vertical distribution of ozone. A substantial diminution in ozone at 40 km should lead to a lessened absorption of UV radiation at that altitude, and therefore a smaller heating effect, and overall cooling of the upper stratosphere. Another potential effect arises through the influence of stratospheric ozone in determining the height and other properties of the troposphere, which in turn determines the depth of convective activity within the lower atmosphere.

III. EVOLUTION OF IONOSPHERIC PHYSICS

An entirely different range of solar-terrestrial effects on society and technology arises through the influence of particle and x-ray ionization on radio propagation. With the advent of communications satellites, operating at frequencies far above those at which ionospheric effects are dominant, much of the earlier importance attached to ionospheric propagation seemed to decrease. In fact, however, recent years have seen an increase in the use of the lower-frequency ranges, from about 10 kHz to 30 MHz, in which ionospheric effects are indeed important. There are several practical reasons for this in-

crease in use, among them the facts that some parts of the earth, particularly in the polar regions, are inaccessible to synchronous satellite links and that the cost and complexity of satellite ground facilities effectively rule them out for many purposes, particularly in the less industrially developed countries.

Ionospherically propagated radio waves are currently being used for a wide variety of purposes, including aircraft communications (especially on trans-polar flight paths), ship-to-shore and ship-to-ship communication, and long-range navigation. Conditions in the lower ionosphere can have an important effect on these applications by causing loss of signal at medium and high frequencies or by changes of phase in the lf and vlf signals that are used for navigational purposes. Major enhancements in ionization occur in association with auroral displays and magnetic storms, but the ionospheric effects tend to be patchy and relatively short in duration. A much more severe problem arises from the so-called polar-cap absorption events in which intense ionization created by solar protons blankets both polar caps down to magnetic latitudes of 60–65° for several days at a time. During these events hf communications at high latitudes are seriously degraded and may even become impossible for long periods of time.

The venerable field of ionospheric physics has been thoroughly penetrated by the results of solar-terrestrial research and has re-emerged, in renaissance, as an accessible cosmic-scale plasma-physics domain whose understanding seems crucial to any advance in our understanding of the exchange of matter, energy, and momentum between the interplanetary medium, the magnetosphere, and the lower atmosphere. The appreciation of the importance of particle energy sources in driving ionospheric dynamics has led to improvements in ionospheric forecasting and may contribute to more efficient use of the frequency bandwidths allocated to various users. Herein lies one of the contributions that solar-terrestrial research can make: while research cannot create additional bandwidths in the already crowded spectrum, continued work in the area of magnetosphere-ionosphere-atmospheric coupling and in the forecasting of ionospheric disturbances can improve the utilization of existing frequency allocations. Such research will provide essential information and trained personnel so that decisions on frequency allocations are based on the best physical understanding available.

The understanding of the role of the small-scale structure of the ionosphere in various communications, navigation, and radar systems has also evolved. Increasing use of satellite communication links and satellite-based navigation systems has focused interest on the characterization of trans-ionospheric propagation of electromagnetic energy and has enhanced interest in understanding the small-scale structures of the ionosphere, which give rise to signal scintillations, even at frequencies in the GHz range.

IV. THE SOLAR-VARIABILITY-WEATHER-CLIMATE CONNECTION: DOES IT EXIST?

No area of solar-terrestrial research has generated so much controversy in recent times as the question of a possible connection between solar activity or variability on the one hand and terrestrial weather and climate on the other. The views of the proponents of a connection find their way into the national press with some regularity, and the controversy has even percolated into the popular press. The opposing view, maintained so far by the mainstream of meteorological thought, has not been so well publicized.

First, we need to distinguish between weather time-scales (hours to months and seasons) and climate time-scales (years to hundreds of millenia). The inertia of the atmosphere-oceans system is such that at the shorter time end of the scale only solar transients could have any effect; on the longer time-scales, variability of the sun's luminosity would dominate; at the intermediate time-scales of long-range weather forecasts, it is conceivable that the cumulative effect of solar activity might play a role.

Second, we need to distinguish between scientific interest in these questions and, if the relationships are shown to be real, the practical utility of applying them to predictions about the weather and climate. Weather predictions will depend on predictions of solar activity and the transmission of the resulting energy, particles, and fields through the sun-earth system. At present, these predictions are largely statistical, with some hours to a couple of days' warning in some cases that something from the sun is coming our way. Even the most enthusiastic partisan of the reality of the solar-activity-weather connection would probably concede that such effects would be lost in the welter of intrinsic meteorological variability, with its much larger amplitudes. The potential solar-activity-*weather* relationship thus appears to be mainly of scientific interest. On the other hand, the question of a potential relationship between solar variability and *climate* is clearly of great practical interest, because the water supply and agricultural systems of the world, or at least large parts of them, appear to be only marginally stable. The ability to predict changes in climate or to predict what the next seasons will bring could be important for economic planning and resource allocation on regional, national, and international scales.

Such evidence as has been presented to support the hypothesis that solar variability affects the weather and climate has been in the form of correlations between parameters that describe solar outputs directly or indirectly (sunspot numbers, interplanetary field reversals, geomagnetic disturbances) and measurements of terrestrial weather and climate (temperature, pressure, precipitation, frequency of thunderstorms). Opponents of these hypotheses question the validity and analysis of the data sets, for example on the grounds that the data are local or regional rather than global; that data that could have

been used, but were not, destroy the correlations; that correlations established for short time-series disappear or change sign when the time-series are extended; and that the results are not subjected to critical tests of their statistical significance.

There is also the problem of physical mechanisms. The mechanisms for linking variability in the sun's luminosity to longer-term weather or climatic change, namely changes in direct heating, is perfectly straightforward. The main difficulty here would be to separate such effects from others of generally accepted validity with comparable time-scales—for example, the buildup of carbon dioxide, or volcanic dust (or, for time intervals comparable with interglacial periods, changes in the earth's orbit). The case is quite different for mechanisms postulated for linking solar activity to weather-scale effects. The latter appeal to various "trigger" mechanisms in which a relatively minute amount of energy can push the unstable weather system off balance. But a quantitative analysis of the efficiency of such mechanisms is difficult, because the coupling of the known solar input to the magnetosphere-ionosphere system with effects in the troposphere proceeds by way of intermediate regions. Steps in these processes are still subject to such great uncertainties that the hypotheses are hard to test.

With an assured flow of both solar-terrestrial and meteorological data, however, and with a growing understanding of the links in the solar-terrestrial chain that might reach into the troposphere, we shall certainly be able to answer questions like the following: Does solar activity or variability affect the weather or climate? If so, how? The Geophysics Research Board's study *Solar Variability, Weather, and Climate* similarly emphasizes the importance of treating the possible influence of solar variations on weather and climate as part of the more general subject of solar-terrestrial and atmospheric physics and stresses the need for development and testing of models of the effects of solar perturbations on the atmosphere. If effects on the lower atmosphere exist and are understood, and if we could predict solar activity and variability, we should be able to estimate their effects on weather and climate, and consequently evaluate the potential impact—possibly the single most important impact—of solar-terrestrial relations on our immediate environment, and thus on society and its technology.

Appendix A: Principal Recommendations of Recent Reports of the National Academy of Sciences Relevant to Solar-Terrestrial Research

We have assembled the conclusions of five recent reports that we regard as being the most generally relevant to solar-terrestrial research.

Space Plasma Physics: The Study of Solar-System Plasmas

In 1976, NASA requested the National Academy of Sciences to undertake a review of space plasma physics to assess its scientific content and NASA's role in this field. The resulting study led to the Space Science Board's report, *Space Plasma Physics: The Study of Solar-System Plasmas* (National Academy of Sciences, Washington, D.C., 1978). We strongly support their recommendations. The following conclusions and recommendations from this report (also referred to as the "Colgate report") are reproduced in full:

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.

The unified recommendations of the Panels on Plasma Physics of the Sun, Solar System Magnetohydrodynamics, and Solar-System Plasma Processes ("advocacy panels") are as follows:

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.

The Colgate report also states:

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.

Solar-System Space Physics in the 1980's: A Research Strategy

Following the Colgate report recommendations, the NAS presented to NASA the report by the Space Science Board's Committee on Space and Solar Physics, *Solar-System Space Physics in the 1980's: A Research Strategy* (National Academy of Sciences, Washington, D.C., 1980), which makes recommendations that implement those in the Colgate report. The present study is in strong agreement with the recommendations of this report (also referred to as the "Kennel report"), and we reproduce here the principal recommendations:

I. RESEARCH PROGRAMS

We recommend a balanced program of research devoted to interactive solar-terrestrial processes. In particular:

For Solar Physics

1. High-resolution observations are needed to advance understanding of active regions and the small-scale velocity and magnetic fields important to the chromospheric and coronal energy balance, as well as of solar flares. These require Shuttle instruments that achieve 0.1 arc sec resolution in the spectral range from below the HI Lyman- α line to the infrared.

2. *In situ* measurements are needed to provide qualitatively new information critical to understanding coronal plasma processes and solar-wind generation. These require a solar flyby or probe that penetrates as close to the sun as possible (4 solar radii seems technically feasible).

3. Space observations lasting a significant portion of the next solar cycle are needed to infer solar interior dynamics from large-scale motions and oscillations at the sun's surface, to study transient events, to observe the large-scale magnetic and plasma structures instrumental in coupling energy to the solar wind, and to monitor solar luminosity. (It may ultimately become necessary in the decades following the 1980's to monitor the effects of color variability on luminosity over several solar cycles.)

For Terrestrial Magnetospheric Physics

To advance quantitative understanding of the time-dependent exchange of energy and plasma between the solar wind and magnetosphere requires six *simultaneous* studies of plasma processes: (1) deep in the earth's magnetic tail; (2) in the solar wind upstream of earth; (3) near the midmagnetosphere equatorial plane; (4) well above one polar cap; and (5) from the ground.

6. A low-altitude polar orbiter is needed to measure the dynamical and chemical response of the atmosphere to magnetospheric variability.

This global research program should be supplemented by active experiments that can increase our knowledge of magnetospheric and plasma processes.

For Terrestrial Upper-Atmospheric Physics

A series of space observations is needed to advance understanding of the interacting dynamical, chemical, and radiative processes in the mesosphere, stratosphere, and thermosphere. One low- and one high-inclination spacecraft are first needed to establish basic atmospheric properties and their geographical, diurnal, and seasonal dependences. Thereafter, magnetospheric coupling processes should again be addressed. Continuing upper-atmospheric observations throughout the 1980's are needed to provide good solar-cycle coverage. Complementary high-resolution studies should be made using Shuttle facilities.

II. EVOLUTION OF SHUTTLE SCIENCE

It is essential that Shuttle-class instruments be kept in space longer than one week at a time. Solar, atmospheric, and magnetospheric Shuttle instruments currently being developed could be combined with a power source to create a free-flying Solar Terrestrial Observatory. This would combine the best present advantages of Shuttle and smaller spacecraft—namely, high resolution and long duration. We recommend that Shuttle solar-terrestrial programs evolve toward such an observatory.

III. THEORY AND INFORMATION HANDLING

Theory has to play an increasingly central role in the planned development of solar-system space physics. Moreover, theory and quantitative modeling should guide its entire information chain—data acquisition, reduction, dissemination, correlation, storage, and retrieval—to a higher level of sophistication, to provide prompt availability of coordinated data of diverse origins.

IV. COORDINATED RESEARCH

Coordinated research is an important general objective of solar-terrestrial physics, which is concerned with time-variable phenomena spanning several regions of space and scientific disciplines.

The research programs proposed above are justifiable on their individual merits. Coordinating them with the approved Solar Polar Mission in particular can greatly increase coverage of the solar-terrestrial interaction.

(a) Detailed examination of the three-dimensional structure of the sun's large-scale magnetic field is made possible by in-ecliptic coronal observations that are simultaneous with those from the solar-polar spacecraft.

(b) Simultaneous in-ecliptic and solar-polar measurements of the solar wind can provide important information about the large-scale structure of solar-wind disturbances. These in-ecliptic measurements can be provided by the interplanetary element of the global magnetospheric study proposed in II.

(c) As we recommended in II, simultaneous measurements in the polar upper atmosphere and the magnetosphere can provide new insight into how solar-wind perturbations couple to upper-atmospheric winds and chemistry.

(d) We believe that such coordination is feasible and, if achieved, would permit the heliospheric and terrestrial response to solar activity to be studied on a solar-system scale.

The NASA research proposed here provides a foundation, and the Solar Polar Mission an optimum time—1986-1987—for coordination of research sponsored by other agencies of the U.S. Government and possibly foreign nations. For example, coordination is critical to provide the ground-based observations recommended in II. We urge that NASA play a prominent role in developing and coordinating a joint program as rapidly as possible.

V. PLANETARY RESEARCH

Measurements of plasmas, fields, and energetic particles must remain integral parts of each planetary mission.

The Upper Atmosphere and Magnetosphere

The third NAS report that we cite, strongly approving its recommendations, is *The Upper Atmosphere and Magnetosphere* (National Academy of Sciences, Washington, D.C., 1977). This study was produced by a Panel of the Geo-

physics Study Committee under the chairmanship of F. S. Johnson. The following are excerpts from its principal conclusions.

... Increasing interest can be expected in the macrophysics of the thermosphere. The Electrodynamic Explorer Program represents a first step in this direction, but *in situ* spacecraft measurements are not ideal for gathering synoptic information on conditions in the upper atmosphere. Simultaneous measurements are needed, and to get these a global network of ground-based upper atmospheric observatories and remote-sensing satellites will be needed.

... The influence of the ionosphere on radio communications therefore remains important. It is even of importance to satellite communications, where small-scale ionospheric irregularities sometimes make communications unreliable even at the high frequencies that are used in such systems.

The upper atmosphere provides a natural plasma laboratory, one with parameters that are often difficult to reproduce in the laboratory. A great variety of plasma instabilities and physical processes have been discovered or demonstrated in the upper atmosphere, thus providing an interchange between the fields of geophysics (including the upper atmosphere, ionosphere, and magnetosphere) and plasma physics. Many of the plasma-physics effects in the upper atmosphere are important to the overall behavior of the ionosphere and magnetosphere. An understanding of these effects is essential in the prediction of many ionospheric effects, including some that are of importance in the field of radio communications.

... how does solar-wind plasma penetrate the magnetic field of the earth, and how is energy transferred from the solar wind so as to drive a global pattern of magnetospheric convection? These questions are about as basic as any that can be asked. *Answers to such questions about the physics of the upper atmosphere and magnetosphere will be forthcoming soon if appropriate efforts are expended.*

Because of the immense size of the magnetosphere-atmosphere system (relative to the size of the earth) and the extent to which processes in one part of the system influence distant parts of the system (mainly by electrical transfer of energy), *coordinated simultaneous measurements are of great importance.*

... the interactions between the magnetosphere and that part of the atmosphere known as the thermosphere, and the overall behavior of the thermosphere as it is pushed one way by solar ultraviolet heating and another by energy input through the magnetosphere (both variable), are subjects on which important progress is to be expected. It has become increasingly clear that weather responds to solar events through physical mechanisms that have

not yet been visualized; they probably involve the magnetosphere and the thermosphere. *The expectation of progress in the area of sun-weather relationships is speculative because physical links have not been identified, but it is an important area to pursue.*

The appropriate means of attack on problems of the thermosphere is with satellites of the Atmosphere Explorer type, two of which are in operation at this time. *The Committee concludes in agreement with the Space Science Board in its report, Opportunities and Choices in Space Science, 1974, that additional satellites of the Atmosphere Explorer type will be needed in the early 1980's. . . .*

. . . Balloons provide an important means of making in situ observations in the stratosphere, and their continued use is important.

. . . Satellites such as those required for thermospheric investigations and the AMPS Shuttle payload are appropriate for attack on F-region problems, and incoherent-scatter radar observations provide a powerful technique on the ground. The Committee recommends that steps be taken to reassert U.S. leadership in the latter area.

. . . rocket programs must be preserved and remote-sensing techniques developed for use in satellites.

. . . investigation of the earth's upper atmosphere and magnetosphere should be considered a part of the foundation upon which planetary and astrophysical investigations are based.

INTERNATIONAL COOPERATION

In many geophysical problems, there is a greater need for international cooperation than in most other fields of science because coordination is required in the making of observations in different parts of the geophysical system that are interrelated by physical processes. Programs are usually arranged through the relevant International Scientific Unions, their parent body, the International Council of Scientific Unions (ICSU), or special committees of ICSU.

The Middle Atmosphere Program: Prospects for U.S. Participation, 1980

The fourth report that we cite is one by the CSTR Panel on the Middle Atmosphere Program, *The Middle Atmosphere Program: Prospects for U.S. Participation* (National Academy of Sciences, Washington, D.C., 1980).

That report recommends, and we strongly endorse (sections cited refer to that report):

1. That a national MAP coordination office be established within an appropriate lead U.S. agency to act as a focal point for planning, implementing, and coordinating a U.S. program for MAP both among the agencies concerned and between those agencies and the scientific community at large. (See Section 2.4 for details.)

2. That the U.S. support the efforts of the international MAP Steering Committee to establish mechanisms for the collection and exchange of information and data on all appropriate time scales. (See Section 2.5 and 3.2 for details.)

3. That the U.S. scientific community in cooperation with the U.S. agencies concerned review the following areas (see Section 3.1 for details) in deciding what investigations to pursue, as these appear to be the areas in which the U.S. can make the most fruitful contributions: Ozone climatology; stratospheric composition; mesospheric composition; basic climatology of the middle atmosphere; planetary waves in the middle atmosphere; equatorial waves; tides, gravity waves, and turbulence; troposphere-stratosphere coupling; the influence of middle-atmospheric conditions on lower-level climate; aerosol formation and properties; solar radiation, especially in the ultraviolet; the effects of energetic particles and x-rays on the middle atmosphere; ion composition; and the electrodynamics of the middle atmosphere. These fourteen areas have been tagged observational or experimental "MAP initiatives" (MIs) and numbered for ready reference.

4. That theoretical studies and modeling be supported. (See Section 3.2, MI-15.)

5. That a program of balloons and rockets that are still required for certain kinds of *in situ* observations and the launch facilities to go with them be supported.

It is clear that these four previous studies will continue to have a significant impact on many aspects of solar-terrestrial research. Many of the specific recommendations in these studies match those of the present CSTR study. Taken together these collected studies point the way toward maximizing scientific progress in STR for the 1980's.

Upper Atmosphere Research in the 1980's: Ground-Based, Airborne, and Rocket Techniques

This fifth report (National Academy of Sciences, Washington, D.C., 1979) is the outcome of a summer study conducted by the CSTR in 1978 under the leadership of F. S. Johnson. That study was the forerunner of the present study, and many of its principal conclusions have been integrated into the present report. We reproduce its principal conclusions below. The order in which they are given does not necessarily reflect their relative priority.

We recommend that an incoherent-scatter radar facility be established [in the subauroral zone] for the observation of a variety of important upper-atmospheric phenomena such as thermospheric winds and ion flows over a range of subauroral latitudes. [The purpose of this recommendation was to study disturbances emanating equatorward from the auroral zone or polar cap.]

We recommend that various options be explored for making incoherent-scatter radar observations at geomagnetic latitude $\Lambda = 76-78^\circ$ and that an appropriate observatory be established at the earliest opportunity. [The purpose of this recommendation is to measure the important energy and momentum sources of the upper atmosphere at the throat of the auroral zone convection pattern, where there is major heat input.]

We recommend that efforts be made to exploit mesosphere-stratosphere-troposphere (MST) radar capability at midlatitudes [where it would be of special value in studying stratosphere-troposphere exchange and transport properties in the stratosphere and mesosphere by sampling as feasible in a few places.]

We recommend that the newly demonstrated capabilities of the [stratosphere-troposphere] ST-radar technique be exploited using existing instrumentation in order to gain a fuller understanding of the importance of small-scale motions to the overall dynamics of the upper troposphere and lower stratosphere. Studies should be undertaken to examine the potential scientific return of a more extensive network of ST radars. Preliminary design studies of a transportable ST radar should be undertaken in order to establish the specifications and cost of an ST radar network.

We recommend that advances in optical technology

recently developed for use on spacecraft be exploited by further development and upgrading of instrumentation for ground-based studies of the energy sources, chemistry, and dynamics of the upper atmosphere.

We recommend that the balloon and sounding-rocket program be preserved during the Space Shuttle era to make important atmospheric measurements that cannot be made from satellites. We further recommend the maintenance and, where required, the expansion of rocket and balloon launch facilities to accommodate the need for data acquisition at various geographical locations.

We recommend that the momentum now established in stratospheric investigations be vigorously maintained. To do this we need to exploit present methods of both in situ and remote sensing of chemically active minor constituents and to develop new methods. We also strongly encourage study and development of methods, particularly those using tracers, for examining the global-scale horizontal movement of air masses within the stratosphere.

We recommend that a program be undertaken to determine the distribution of mesospheric constituents. Relevant photolysis rates should also be measured.

We recommend that more observational and theoretical studies be devoted to the stratosphere-troposphere interchange process and that fast-response instrumentation be developed for measurements of chemical constituents such as O_3 , H_2O , and CO in support of these studies.

We recommend investigation of atmospheric electric fields of magnetospheric, ionospheric dynamo, and thunderstorm origin to determine their role in middle atmospheric transport and chemical processes.

The report contains some 20 additional recommendations that were accorded somewhat lower priority.

Solar Variability, Weather, and Climate, 1980

A comprehensive study of the evidence on influences of solar variability on weather and climate has been commissioned by the Geophysics Study Committee of NRC's Geophysics Research Board. This study on *Solar Variability, Weather, and Climate* is being prepared by a panel under the chairmanship of J. A. Eddy. It provides an important complement to this present study, and to the reports cited above, by pursuing the specific question of solar variability influences on the troposphere. We paraphrase below the main conclusion of this study now in preparation.

A central focus of this study is the great interest of improving our *physical* understanding of the influences of solar variability on the complex scheme of factors that determine weather and climate. The scientific interest in isolating subtle effects of variable solar inputs on the troposphere will remain, even if future research were to demonstrate that the effects of solar variability itself are too small to be of *practical* use in understanding past climate changes or in predicting changes in the future.

The study notes that important advances have been made in our understanding of both the variability of solar outputs and also the sources of weather and climate change since early attempts to correlate the sunspot cycle with local weather. This evolution in our knowledge suggests certain basic changes in our approach to the problem.

On the one hand, it now appears likely that predictable changes in the earth's motion around even an unchanging sun could produce variations of climate with the power spectrum and phase of the major ice ages. Advances in climate dynamics also lead us to a better appreciation of the many complex internal feedbacks within the atmosphere-ocean-continent system itself that could produce quasi-periodic oscillations on time scales that overlap those observed in solar magnetic activity.

At the same time, the many aspects of variable solar outputs in electromagnetic waves, charged particles, and magnetic fields have been much better understood. We now see clearly that the sunspot number is only loosely connected to changes in some important solar outputs, such as ultraviolet radiation. It is a poor estimator of other important outputs such as particle fluxes.

The complexity of the sun-earth system, revealed to us through gradual accumulation of careful observations and theoretical explanation, strongly suggests that a continuing quest for simple correlations between randomly chosen weather variables and solar indices is unlikely to be fruitful.

The study recommends that the newly acquired understanding of well-defined variable solar influences on the magnetosphere and upper atmosphere be used to reformulate the classical sun-weather question as a properly defined physical problem within the context of modern solar-terrestrial physics.

The process of measurement and theoretical evaluation promises to be intellectually stimulating, since the mechanisms in question will surely stretch our knowledge of the many elements of the solar-terrestrial system and of their interfaces. This broadly based cooperative endeavor between the individual disciplines of solar-terrestrial physics cannot fail to yield new insights into the operation of the individual elements themselves. It is possible that the results will also reveal a sun-climate link (or several) that would prove to be of immense practical utility to mankind.

Particular attention needs to be directed toward the formulation of consistent physical mechanisms to explain the better established existing connections between solar or interplanetary variables and tropospheric parameters. Moreover, future empirical studies must be guided first by careful choice of physical variables whose changes can be related to climate and weather through realistic dynamical models.

