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

Committee on Solar and Space Physics
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Foreword

This is one of a series of documents prepared by committees of the Space Science Board (SSB) that develop strategies for space science for the coming decade. The Board has already issued several such reports: *Report on Space Science 1975* (Part II, Report of the Committee on Planetary and Lunar Exploration, which covers the outer planets), *Strategy for Exploration of the Inner Planets: 1977-1987* (1978), *A Strategy for Space Astronomy and Astrophysics for the 1980's* (1979), and *Life Beyond the Earth's Environment* (1979). Other reports are in preparation on earth sciences; relativity and gravitational physics; the primitive smaller bodies in the solar system; and planetary biology and chemical evolution.

This report develops a scientific strategy for solar and space physics for the 1980's. It focuses on the programs, experiments, and instruments that will be required to continue progress, on a broad front, toward answering the many important and varied scientific questions that have been identified as the goals we hope to achieve.

The strategy was developed as a continuation of the Board's assessment of the future objectives of space-physics research that was begun with the Colgate study (*Space Plasma Physics: The Study of Solar System Plasmas*, National Academy of Sciences, Washington, D.C., 1978). A main conclusion of that study was that "theory should play a central role in the planned development of the field." The Board's Committee on Solar and Space Physics was therefore charged with continuing the effort by developing the required experimental component of the research program utilizing appropriate theoretical input.

This strategy report has been adopted by the SSB as its policy for solar and space physics, and it supersedes all previous reports dealing with the experimental program in space physics.

The development of this strategy has been a long and difficult task. The Board owes a great debt to the members of the Committee for their diligent and untiring efforts and particularly appreciates the contribution of the Chairman, Charles F. Kennel, under whose direction this report has been brought to fruition.

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

Acknowledgments

We are grateful to many individuals and institutions too numerous to mention. Special thanks go to the Jet Propulsion Laboratory; Goddard Space Flight Center; the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles; the Marshall Space Flight Center; and the National Center for Atmospheric Research, who hosted the meetings during which we prepared this strategy. The Committee on Solar and Space Physics met jointly with the Committee on Solar-Terrestrial Research (CSTR) of the Geophysics Research Board at Huntsville in October 1978 and thanks CSTR and its chairman, A. Nagy, for their help and interest. Harold Glaser and David Stern of NASA readily provided us with critical information whenever asked. A. G. W. Cameron, chairman of the Space Science Board, gave us important guidance at each step in the formulation of this strategy. Many of our colleagues commented on drafts of this document. Finally, we thank our Executive Secretary, Richard C. Hart, whose untiring efforts on behalf not only of this strategy but also of the Study Committee on Space Plasma Physics have been a valuable service to our science.

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1 Introduction

The sciences we now collectively call solar and space physics began their development early in the history of Western thought. The ancient Greeks were puzzled by the "fire" in the upper atmosphere that we now call the aurora polaris. Galileo discovered sunspots in 1612, and in the succeeding century it was established that the number and size of sunspots increased and decreased with an approximately 11-year period. Moreover, there proved to be correlations between the spots on the sun, the intensity and location of the aurora, and fluctuations in the earth's magnetic field. Until recently, neither experimental nor theoretical understanding was sufficient to provide any reason based in physics for the mysterious relationship between activity at the surface on the sun and auroral and magnetic activity at earth.

Twenty years of space research have given us a basis to address this relationship. The earth has an atmosphere, above the one we breathe, made of electrically conducting ionizing gas–a plasma. Since the earth's magnetic field controls the structure of this plasma atmosphere, we call it the magnetosphere. The sun's outer atmosphere–the corona–generates a magnetized plasma wind that blows throughout interplanetary space and interacts with each of the planets. At earth, this interaction causes strong highly variable motions within the magnetosphere and fills it with solar-wind plasma. Recently, we have begun to understand how the solar wind is related to the structure of the magnetic fields in the corona and to the processes generating these fields in the solar interior. Moreover, we have realized that solar-wind-generated magnetospheric activity drives strong winds in the earth's upper atmosphere. Thus, whereas once we knew only that auroras intensify when there are sunspots, we now perceive the chain of interactions that links events at the sun's surface to the solar wind and, hence, to the magnetosphere and atmosphere, only one of whose consequences is the aurora. This interaction chain may extend deeper into the atmosphere. Whereas 10 years ago it was generally believed that significant effects of solar variability penetrate only as far as the upper atmosphere, some scientists now suggest that they also reach the lower atmosphere and so affect weather and climate in ways not yet understood. Although the sunlight intercepted by the earth is the only obvious agent connecting the sun with weather and climate, the question of a more subtle solar-terrestrial influence, while still controversial, is so important that we must try to answer it.

The discovery of the earth's radiation (Van Allen) belts in 1958, and of the solar wind in 1960, made it clear that the exploration and future understanding of the sun's and earth's space environment would be couched in part in terms of plasma physics—a discipline of physics that had lain relatively dormant until called forth by human need and curiosity. Since 1960, plasma physics has developed in two separate but parallel directions. Controlled thermonuclear fusion research seeks a source of clean energy that can last for a time comparable with the present age of the earth; the main obstacle to achieving controlled fusion lies in our imperfect understanding not of nuclear physics but of plasma physics. Solar-system space research seeks useful comprehension of nature's processes on a global, indeed a solar-system, scale, in recognition of man's intimate and sensitive dependence on his environment. It is both symbolically and substantially significant that the same discipline—plasma physics—defines a basic language used in both fusion and space research.

Space observations, and a growing understanding of plasma physics, are bringing to a close a long preliminary phase of phenomenological research. Solar-system space research is becoming a quantitative science. As a consequence, it is now yielding useful understanding of solar-terrestrial effects on technological systems in space and on earth. One example is understanding the effects of ionospheric variability on radio communication. Another is understanding the disruptions of electric power grids and pipeline monitoring systems, and the spacecraft component failures, that take place during magnetic storms. The increasingly quantitative nature of our understanding also means that solar-system space research now makes important contributions to basic plasma physics, in areas such as magnetic field-line reconnection, which is thought responsible for explosive energy releases in solar flares, magnetospheric substorms, and fusion devices.

Twenty years of space research have taught us that the physical processes that we study at the sun, in the solar wind, and at the earth, occur throughout the solar system and indeed the astrophysical universe. We now study the interactions between the planets (and comets) and the solar wind in mutually reinforcing ways. Our experience with the earth's magnetosphere was essential first to design the recent Pioneer and Voyager studies of Jupiter's magnetosphere and then to understand their results. Understanding how the sun and planets generate their magnetic fields may help to explain why magnetic fields are so prevalent throughout the universe. Stars like the sun that have convective outer layers are inferred to have stellar winds; more massive stars have winds driven by radiation pressure. Plasma winds may also be generated in globular clusters and galactic halos; relativistic winds have been proposed for pulsars and radio galaxies. Thus, the term "magnetosphere" is used not only for the earth and planets but also for the environments of x-ray sources, pulsars, and radio galaxies.

The solar system offers an excellent laboratory in which large-scale processes involving flowing plasmas and magnetic fields pertinent to astrophysics can be studied *in situ*. Moreover, many microscopic processes that are important to astrophysics, such as those accelerating charged particles to high energy, will probably remain forever unobservable by remote techniques. However, the analogous processes occurring in solar-system plasmas can be studied *in situ*.

Above are a few reasons why we believe that solar-system space research should be kept vigorous. What follows is a strategy for so doing.

2
Guiding Principles

Two basic principles guided the design of the strategy:

- *The objectives of solar-system space research are to understand the physics of the sun; the heliosphere; and the magnetospheres, ionospheres, and upper atmosphere of the earth, other planets, and comets.*
- *Studies of the interactive processes that generate solar variation and link it to the earth should be emphasized, because they reveal basic physical mechanisms and have useful applications. Quantitative understanding of the solar-terrestrial interaction chain can provide a better basis for answering the question of whether solar variability affects weather and climate.*

3
Status and Objectives

Here we summarize the discussion in Part III of the recent accomplishments and present status of our subdisciplines. In addition, we define objectives that can motivate research programs in the 1980's.

SOLAR PHYSICS

Major advances in our understanding of the sun were made in the 1970's (see Figure 1A). For example, new approaches to the related problems of convection and the generation of the sun's magnetic field were pioneered. Most, if not all, of the magnetic flux that emerges from the convective zone was found to do so in small regions of strong (1200–2000 G) field, a fact that is still not understood theoretically. Observations confirmed earlier predictions that the 5-minute photospheric oscillation, discovered in the early 1960's, is a global phenomenon. This has made "solar seismology" possible, by which the depth of the convective zone, and the rotation gradient below the photosphere, can be inferred. Direct checks on interior rotation by solar quadrupole moment measurements may also be possible in the future. In addition, by ruling out the classical model of coronal heating by acoustic waves, observations from the ground and from OSO-8 raised anew the question of what maintains the corona's high temperature. Coronal holes were one of the major discoveries of the 1970's. White-light, EUV, and x-ray observations suggested how coronal holes are related to the convective zone and to the solar wind. ATM unambiguously identified close magnetic arches as the basic observed coronal structure of coronal flares. This perception altered our theoretical picture of

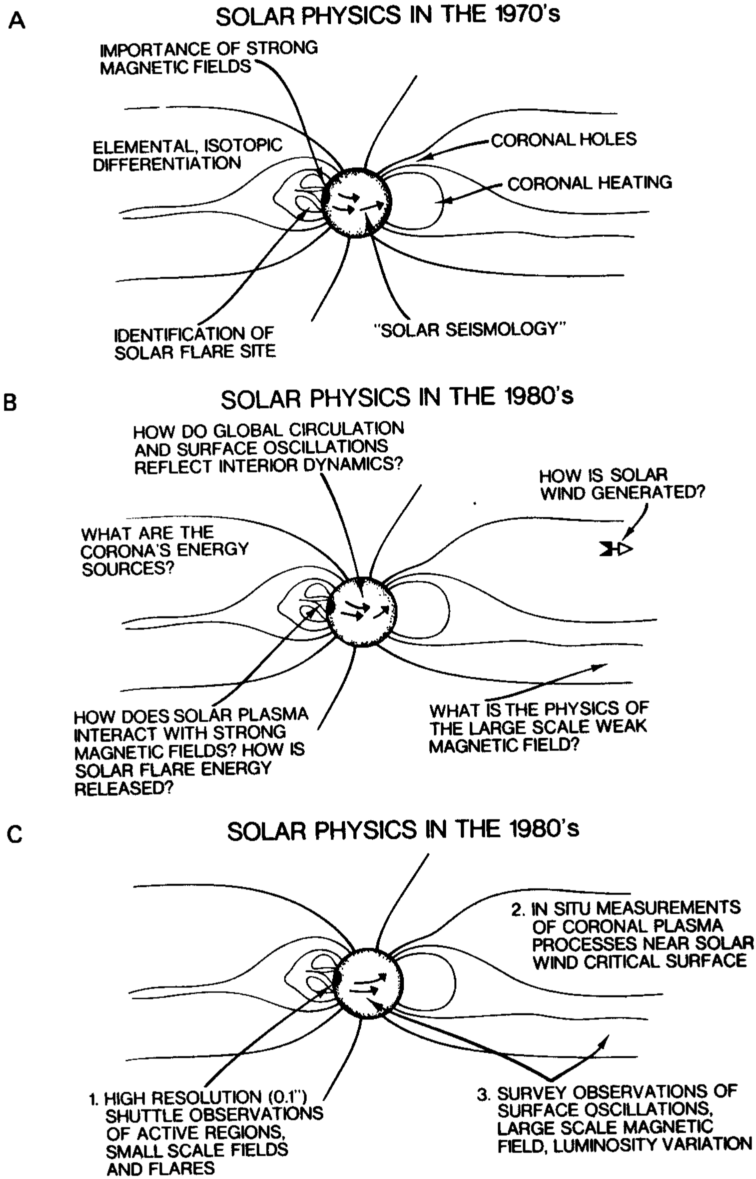

FIGURE 1 Solar physics: status, objectives, and recommendations. In this series of sketches of the sun and its coronal magnetic field we illustrate some recent accomplishments in solar physics. A, Questions that can be fruitfully attacked in the 1980's, B, and the principal research programs needed to answer these questions. C, Shown here is the sun and solar corona within 5 solar radii. The influence of the processes occurring within this region extends throughout interplanetary space via the solar wind.

solar flares and illustrates the need for a coordinated multi-instrument attack on them, beginning with the 1980 Solar Maximum Mission. The discovery of local differentiation in the elemental and isotopic composition of the solar atmosphere has changed our perception of global solar composition, with important consequences for models of the solar interior.

To understand better all the processes linking the solar interior to the corona, we need to study (see Figure 1B) the following:

- The sun's global circulation, how it reflects interior dynamics, could modify luminosity, and is related to the solar cycle;
- The interactions of solar plasma with strong magnetic fields–active regions, sunspots, and fine-scale magnetic knots–and how they cause the release of solar-flare energy to the heliosphere;
- The solar corona's energy sources and the physics of its large-scale weak magnetic field.

PHYSICS OF THE HELIOSPHERE

The heliosphere is the plasma envelope of the sun. It extends from the solar corona, where the solar wind first becomes supersonic, to a distance of perhaps several hundred astronomical units (A.U.), where the solar wind is thought to be decelerated by its interaction with the interstellar medium.

The solar wind has been studied near the earth since 1961. In the past decade, measurements of the solar wind in the ecliptic plane were extended to within Mercury's orbit (0.3 A.U.) and beyond Saturn's (9.5 A.U.). Quantitative models of high-speed solar-wind streams and flare-produced shocks were developed and tested against data obtained near the ecliptic. The realization that high-speed streams originate in the rapidly diverging magnetic-flux tubes of coronal holes reoriented much solar-wind research. The sector structure of the solar wind was related to a magnetic neutral sheet of solar-system scale that connects to the large-scale magnetic field of the rotating sun. Finally, microscopic plasma processes were shown to regulate solar-wind thermal conduction and diffusion and, possibly, local acceleration of particles in solar-wind structures.

To understand better the transport of energy, momentum, energetic particles, plasma, and magnetic field through interplanetary space we need to study the following:

- First and foremost, the coronal processes that govern the generation, structure, and variability of the solar wind;
- The three-dimensional properties of the solar wind and heliosphere;

• The plasma processes that regulate solar-wind transport and accelerate energetic particles throughout the heliosphere.

MAGNETOSPHERIC PHYSICS

New processes regulating earth's magnetic interactions with the solar wind were discovered in the 1970's (see Figure 2A). For example, unsteady plasma flows that apparently originate deep in the geomagnetic tail and deposit their energy in the inner magnetosphere and polar atmosphere were observed. Observations of impulsive energetic particle acceleration suggested that the cross-tail electric field is also highly unsteady. The discovery of energetic ionospheric ions in the near tail and inner magnetosphere forced a re-evaluation of our ideas concerning the origin and circulation of magnetospheric plasma.

Our understanding of many individual processes became more quantitative. The coupling of magnetospheric motions and energy fluxes to the thermosphere was observed and modeled. Currents flowing along the earth's magnetic field and connecting the polar ionosphere to the magnetosphere were found to create strong localized electric fields at high altitudes. These fields may accelerate the electrons responsible for intense terrestrial radio bursts and auroral arcs. Thus, the problem of auroral particle acceleration is nearing quantitative understanding. By contrast, the relationship between energy circulating in the magnetosphere, the energy dissipated in the atmosphere, and the state of solar wind could not be understood much more quantitatively in 1979 than in 1969.

To understand better the time-dependent interaction between the solar wind and earth we need to study (see Figure 2B) the following:

• The transport of energy, momentum, plasma, and magnetic and electric fields across the magnetopause;
• The storage and release of energy in the earth's magnetic tail;
• The origin and fate of the plasma(s) within the magnetosphere;
• How the earth's magnetosphere, ionosphere, and atmosphere interact.

UPPER-ATMOSPHERIC PHYSICS

The upper atmosphere has traditionally been divided into the stratosphere, mesosphere, thermosphere (and ionosphere), and exosphere, in order of increasing altitude. Recent research makes it clear that these layers—and their chemistry, dynamics, and transport—are coupled (see Figure 3A). For example, downward transport from the thermosphere can be a source of nitrogen

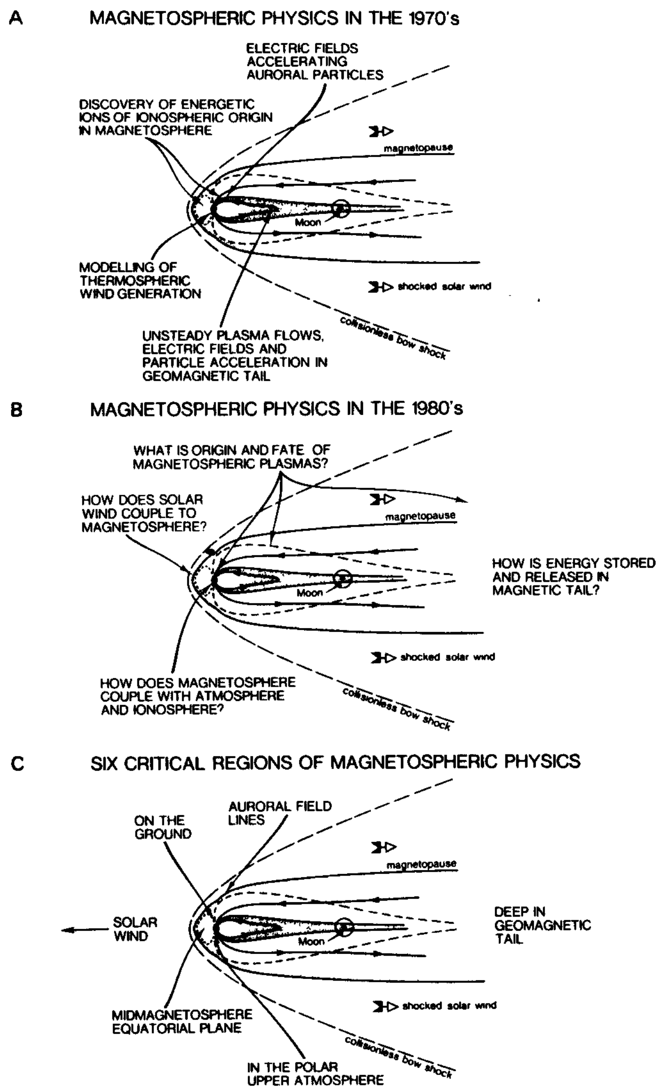

FIGURE 2 Magnetospheric physics: status, objectives, and recommendations. Shown here is the earth's magnetosphere—the cavity formed by the interaction of the solar wind with the earth's magnetic field. A collisionless bow shock stands upstream of the magnetopause, the boundary separating shocked solar wind from the magnetosphere proper. The moon is 60 earth radii from the earth; the earth's magnetic tail is thought to extend some thousand earth radii downstream. A, Illustrates some recent achievements in magnetospheric physics; B, objectives that can motivate research programs in the 1980's. C illustrates the six critical regions where simultaneous studies are needed to help construct a global picture of magnetospheric dynamics.

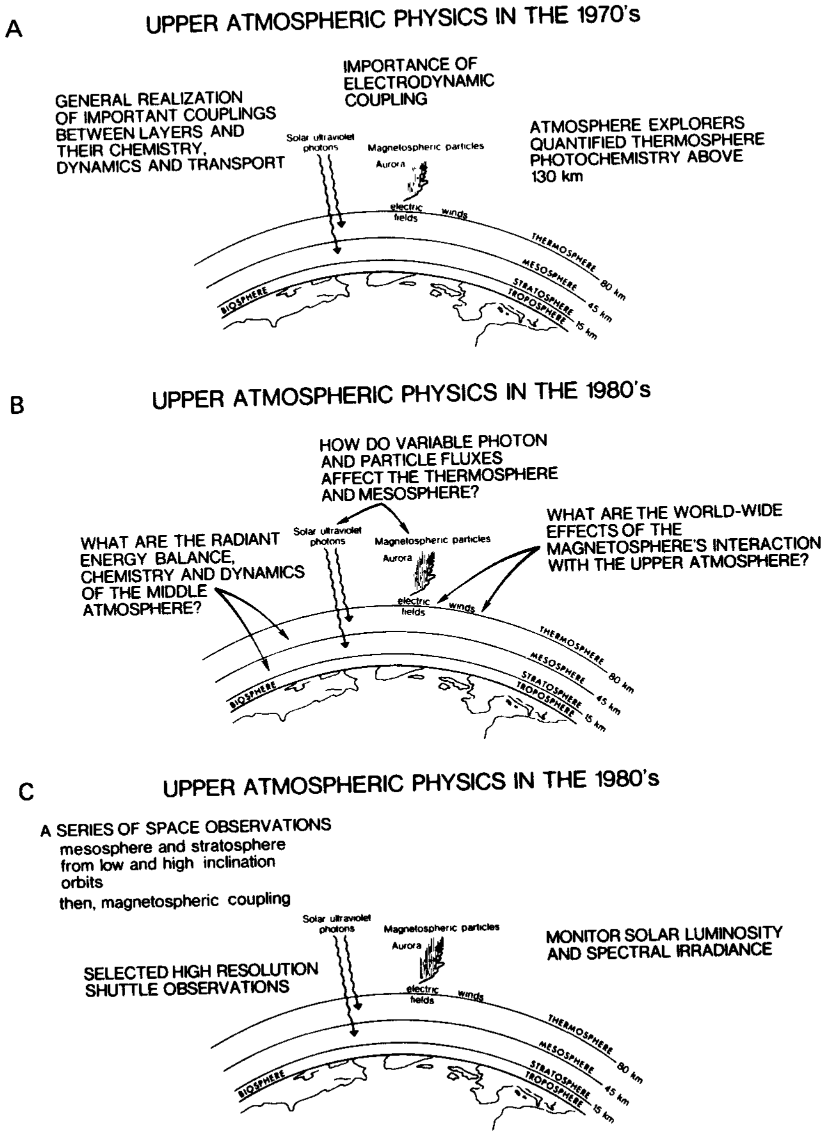

FIGURE 3 Upper-atmospheric physics: status, objectives, and recommendations. Sketched in these figures are the layers into which the atmosphere has traditionally been divided. Our studies of these layers, and the interacting processes occurring within them, are becoming more integrated. Solar-ultraviolet photons deposit their energy largely in the stratosphere and above. The magnetosphere interacts with the upper atmosphere both through energetic plasma deposition and through electric fields, which are generated by magnetospheric motions. Plasma heating and electric fields both couple to upper-atmosphere winds.

compounds to the mesosphere and possibly to the upper stratosphere. The catalytic reactions of odd hydrogen, nitrogen, and chlorine compounds destroy ozone, thereby altering the absorption of solar ultraviolet radiation. Results from three Atmospheric Explorers, which largely quantified the photochemistry of the thermosphere and ionosphere, also illustrated the strength of the electrodynamic coupling of the thermosphere to the magnetosphere. Finally, understanding how the upper and lower atmospheres affect each other will be necessary to understand the complete chain of solar-terrestrial interactions. This will require considerable improvement in our understanding of the chemistry, dynamics, and radiation balance of the mesosphere and stratosphere, as well as of troposphere-stratosphere exchange processes.

To understand better the entire upper atmosphere as one dynamic, radiating, and chemically active fluid, we should study (see Figure 3C) the following:

- The radiant energy balance, chemistry, and dynamics of the mesosphere and stratosphere and their interactions with atmospheric layers above and below;
- The worldwide effects of the magnetosphere's interaction with the polar thermosphere and mesosphere and the role of electric fields in the earth's atmosphere and space environment;
- The effects of variable photon and energetic particle fluxes on the thermosphere and on chemically active minor constituents of the mesosphere and stratosphere.

SOLAR-TERRESTRIAL PHYSICS

Solar-terrestrial physics is concerned with the response of the earth's magnetosphere, ionosphere, and atmosphere to solar variability. For example, a solar flare produces both a strong solar-wind shock that initiates a magnetic storm when it passes over the magnetosphere and energetic protons that penetrate deep into the polar atmosphere. Studies of such solar-terrestrial phenomena are of considerable practical importance.

To understand better the effects of the solar cycle, solar activity, and solar-wind disturbances upon earth, we need to

- Provide to the extent possible simultaneous measurements on many links in the chain of interactions linking solar perturbations to their terrestrial response;
- Create and test increasingly comprehensive quantitative models of these processes.

Whereas 10 years ago it was generally believed that significant effects of solar variability penetrate only as far as the upper atmosphere, some people now believe that they also reach the lower atmosphere and so affect weather and climate in ways not yet understood. For example, it has recently been suggested that the mean annual temperature in the north temperate zone followed long-term variations of solar activity over the past 70 centuries.

To clarify the possible solar-terrestrial influence on earth's weather and climate, we need to

- Determine if variations in solar luminosity and spectral irradiance sufficient to modify weather and climate exist;
- Ascertain whether any processes involving solar and magnetospheric variability can cause measurable changes in the earth's lower atmosphere;
- Strengthen correlation studies of solar-terrestrial, climatological, and meteorological data.

COMPARATIVE PLANETARY STUDIES

Comparative studies of the interaction of the solar wind with planets and comets highlight the physics pertinent to each and put solar-terrestrial interactions in a broad scientific context. The solar system has a variety of magnetospheres sufficient to make their comparative study fruitful. Because the planets and their satellites have different masses, rotation periods, surface properties, and atmospheric chemistry, dynamics, and transport, comparative atmospheric studies can help us to understand atmospheric processes in general and possibly to identify terrestrial processes that might otherwise be missed.

In the 1970's, Pioneer and Voyager spacecraft made flyby studies of Jupiter's atmosphere and magnetosphere, the largest and most energetic in the solar system. The Voyagers will encounter Saturn in 1981. Mariner 10 flybys discovered an unexpected, highly active magnetosphere at Mercury. Pioneer Venus results suggest that the strong interaction between the solar wind and Venus' upper atmosphere plays a significant role in the evolution of the atmosphere.

To understand better the interactions of the solar wind with solar-system bodies other than earth, and from their comparison learn about astrophysical magnetospheres in general, we need to

- Investigate *in situ* Mars' solar-wind interaction in order to fill an important hole in comparative magnetospheric studies—previous missions provided little such information;
- Make the first *in situ* measurements of the plasma, magnetic fields, and neutral gases near a comet;

- Increase our understanding of rapidly rotating magnetospheres involving strong atmospheric and satellite interactions, by orbital exploration of Saturn;
- Illuminate the role of atmospheres in substorms and other magnetospheric processes by orbital studies of Mercury—the only known magnetized planet without an atmosphere.

4
Principal Recommendations

Here we summarize our principal recommendations. More detailed recommendations may be found in Part II.

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.

II
Detailed
Research Strategy

5

Solar and Heliospheric Physics

BACKGROUND

The Orbiting Solar Observatories, OSO-7 and -8, observed solar activity at UV, x-ray, and gamma-ray wavelengths during much of the last solar cycle. The Solar Maximum Mission will observe flares and other high-energy phenomena at the next solar-cycle peak expected in 1980. Intensive coordination of Skylab measurements illuminated the roles played by the large-scale magnetic field, coronal holes, and varying magnetic flux in the evolution of solar-wind structures.

Detailed measurements of the in-ecliptic solar wind are currently being made by the Interplanetary Monitoring Platforms, IMP-7 and -8, and ISEE-3 near the earth's orbit, and Pioneers 10 and 11 and Voyagers 1 and 2 in the outer solar system. The two-spacecraft Solar Polar Mission (SPM) will significantly advance studies of the three-dimensional structure of the solar wind, heliosphere, solar surface, and corona.

BALANCE BETWEEN INTENSIVE STUDIES AND SURVEYS

Centuries of ground-based—together with more recent space—observations have provided us a good grasp of the sun's fascinating phenomenology. However, as recent experience illustrates, the spatial and temporal resolutions achievable on small free-flying spacecraft do not permit truly quantitative study of many solar processes. Even the Solar Maximum Mission will not, in all likelihood, resolve the site of solar flares. Moreover, our remote sensing has not been complemented by *in situ* measurement, because we lack important information that can only be provided by *in situ* measurement. Therefore, intensive high-resolution and *in situ* studies of the solar surface, corona, and the generation region of the solar wind are of prime importance in the near future. On the other hand, studies of global magnetic and velocity fields and of propagation of energy from the solar interior to the corona require long-term syntopic observations. Surveillance of the sun is important to solar-terrestrial studies. We therefore encourage a continuing balance between high-resolution and *in situ* studies and global surveys.

SHUTTLE OBSERVATIONS

Improvements in spatial resolution will lead to major advances in solar physics. The Shuttle can orbit heavy high-resolution instruments, such as the multi-user Solar Optical Telescope (SOT), which can achieve 0.1 arc sec (70-km) resolution in the optical and ultraviolet, a factor of 3 improvement over the best obtainable from the ground. It took the last hundred years to improve ground-based resolution by a factor of 3. It is even more important that continuous high-resolution observations can be made for hours with SOT, instead of the fraction of seconds possible from the ground. When SOT achieves 0.1 arc sec resolution in the visible, operates over the spectral range from below the HI Lyman-α line to the infrared, has a field of view large enough to see the largest active regions, and can simultaneously accommodate various focal-plane instruments, it will dramatically advance many subjects, such as solar flares, active regions, and the small-scale magnetic and velocity fields important to the chromospheric and coronal energy balance. *Since the Solar Optical Telescope should be the central element of Shuttle solar science in the next decade, we recommend that its development proceed with high priority.*

The SOT will only be as powerful as its focal-plane instrument complement. For the earliest SOT flights, this should be drawn from the pool of available Spacelab Principal Investigator (PI)-class instruments. Careful problem-oriented selection and use of SOT PI-class focal-plane instruments, bearing in mind such factors as timing relative to complementary free-flyer investigations and expected solar activity levels, will obtain the best scientific results.

Multi-user facilities will be the main drivers for Shuttle science in the 1980's. At this time, optical and hard-x-ray facility definition teams have finished their work. SOT is indeed appropriate as a multi-user facility, whereas the hard x-ray imaging instrument will be considered on its merits as a PI-class instrument. The definitions currently in progress of soft-ray, XUV, and EUV facilities should be pursued to a logical conclusion.

A pinhole–coronagraph facility is an attractive *new* possibility. Gamma-ray imaging is needed to determine the location, size, and structure of the nucleon acceleration and precipitation regions of solar flares; similarly, the electron acceleration region requires hard x-ray imaging. A pinhole system makes gamma-ray imaging with better than 10 arc sec resolution and hard x-ray imaging with about 1 arc sec resolution possible. In concept, it consists of a large disk with multiple apertures separated from a detector platform containing hard x-ray, gamma-ray, neutron, and other detectors. The disk can also be used as an occulter for a coronograph to achieve, simply, a spatial resolution of better than an arc second–higher than that possible from free-flyers. Such an instrument could examine, for example, the nature of the small-scale turbulent coronal magnetic fields previously identified by radio techniques and the role of the recently discovered stochastic mass flow in coronal streamers. For these reasons, and because of its astrophysical potential, the pinhole–coronagraph concept should continue to be developed.

Development of a pool of PI-class instruments compatible with Spacelab could significantly strengthen observational solar physics, provided multiple flights are available. Instruments selected for Spacelabs 1 and 2 include an ultraviolet telescope and spectrograph and devices to measure magnetic and velocity fields, coronal helium abundance, and the solar constant. Such instruments can be flown in problem-oriented configurations together with one or more multi-user facilities. We recommend that both theoreticians and observers from the solar-physics community at large play an active role in defining these configurations and that the Solar Physics section of the *Report on Space Science 1975* (National Academy of Sciences, Washington, D.C., 1976, page 147) be a guide to the choice of problems.

Many solar phenomena have intrinsic time scales exceeding the one week planned for initial Shuttle flights. The 27-day solar rotation period or the year time scales over which solar cycle variations manifest themselves are two examples. Moreover, longer observing periods are important even for short time-scale phenomena, in part because they permit accumulation of adequate statistics. Thus, extending the observing period available to Shuttle-class solar instrumentation satisfies simultaneously the currently incompatible needs for high-resolution and long-term global observations.

FREE-FLYING SPACECRAFT

Our knowledge of coronal plasma processes consists largely of plausible inferences drawn from remote observations. *Only in situ measurements can establish the coronal plasma state definitely.* Measurements of the solar wind have been made only beyond Mercury's orbit, 80 solar radii (0.3 A.U.) from the sun. Even beyond Mercury, we have caught glimpses of phenomena that might be involved in the generation of the solar wind. (For example, the intensity of hydromagnetic and plasma-wave turbulence increases sharply with decreasing distance from the sun.) However, it is risky to extrapolate our findings to where the solar wind is thought to be generated. *In situ measurements near the solar-wind supersonic transition region are the most direct route to understanding how the solar wind is generated.* For at least these reasons, measurements made near the sun can initiate a new phase in the study of the sun and solar wind, and particularly of their plasma processes.

The first *in situ* determinations of the density, temperature, velocity, and composition of the solar wind near its subsonic-supersonic transition region; the large-scale weak magnetic field, coronal electron and hydromagnetic wave heat fluxes; energetic particle energy, angular, and mass spectra; and plasma-wave turbulence will provide qualitatively new information critical to understanding the coronal energy balance, solar-wind generation, and solar cosmic rays.

In situ measurements might achieve high effective spatial resolution. Available instruments that have 0.1-sec temporal resolution can resolve 35-km distances along a trajectory with a 4-solar radii perihelion. This projects to less than 10 km at the solar surface—finer resolution than that thought possible with remote techniques. Certain remote observations when made near the sun can achieve higher spatial resolution than can SOT. These should be carried out to the extent that they complement, and do not compromise, *in situ* measurements.

Our experience with planetary exploration strategy suggests that the first solar mission should be a flyby (or probe) dedicated to *reconnaissance*—to make new measurements obtainable in no other way, define objectives for future intensive study, and evaluate potential hazards. Thus, it should emphasize its encounter phase and penetrate as deep into the corona and as close to where the solar wind becomes supersonic as conservative estimates of thermal, radiation, and other hazards permit. Multiple encounters are desirable. A science definition team should be formed soon, to permit a flight in the 1980's. A successful mission to the sun could well motivate a larger program of *in situ* studies in the 1990's. Therefore, a preliminary strategy for a series of missions should also be formulated, to help to define the first as part of a logical sequence.

There will be a need for space observations that last for a significant fraction of the next solar cycle to (1) study solar outbursts and relate them to their heliospheric and terrestrial response; (2) infer solar interior structure and dynamics through study of large-scale motions and oscillations at the solar surface; and (3) make in-ecliptic coronal observations complementary to those made on the Solar Polar Mission, and thereby enable detailed examination of the global magnetic field in three dimensions. Studies of large-scale motions and global oscillations sufficient to discern evolutionary trends with adequate statistics require observing periods of at least days to weeks repeated at different phases of the solar cycle. Similarly, observations of the large-scale magnetic field should last several 27-day solar rotation periods and be repeated during the solar cycle.

The above objectives can best be met by earth orbital observations whose duration includes the 1987 polar passage of the Solar Polar Mission. We recommend that detailed mission definition proceed with high priority. The day-night cycle on conventional low-inclination orbits can seriously degrade measurements of large-scale motions and global oscillations, among others. Thus various orbital options, such as sun-synchronous polar orbit, dual spacecraft 180° apart, or an orbit about the sun-earth Lagrangian point should be investigated. In addition, one should determine whether such measurements can best be made on an independent free-flyer or as part of a solar-terrestrial observatory.

The Solar Polar Mission (SPM) will measure the solar wind and cosmic rays out of the ecliptic plane and make stereoscopic remote-sensing observations of the sun for the first time. Because of its intrinsic importance and because coordination with it of other missions proposed here enhances coverage of the solar-terrestrial interaction, it is essential that the SPM project continue to progress in an orderly fashion.

In-ecliptic cruise-mode observations made by planetary missions continue to increase our understanding of the solar wind and the heliosphere, particularly in the outer solar system. Measurements at various points in the ecliptic plane correlated with those over the solar poles made by the SPM will test models of the propagation of solar-wind disturbances and cosmic rays on the scale appropriate to these problems—that of the solar system. Thus, it is important that cruise-mode observations continue.

INSTRUMENT DEVELOPMENT, ROCKETS, AND BALLOONS

High-resolution Shuttle instrumentation should continue to be improved. Objectives for the next decade include sub-arc-second resolution in the extreme ultraviolet and soft x rays, about an arc second in hard x rays, and a few arc seconds in gamma rays. Advances in spatial resolution and sensitivity should be applied quickly to solar flares, because we have no firm indication of the size of their particle acceleration and impact regions.

In the past, rockets and balloons have not only provided the first measurements of many solar phenomena, such as flare hard x rays, but have also been used to test and develop instruments. This approach to instrument development should continue to be considered.

GROUND-BASED OBSERVATIONS

Many phenomena span several layers of the solar atmosphere, some of which are readily observable from the ground. Optical observations will continue to contribute significantly to studies of global magnetic and velocity fields in the photosphere; the response of the photosphere, chromosphere, and corona to solar flares; and other problems. Meter, centimeter, and millimeter radio observations are useful in the study of a wide range of solar variations—ranging from coronal notes to flares. Observations with very high spatial resolution by the Very Large Array (VLA) will provide important new information on the flare process and active regions. Ground observations of the solar neutrino flux are important not only to solar physics but also to nuclear astrophysics in general.

Coordination of space and ground-based research in solar physics—by means such as coordinated observing programs and guest investigators—will not only enhance space studies but will also increase the meaning of the long record of ground observations. The support of existing national centers and university observatories must be sufficient to allow regular development of new instrumental facilities, for this and other equally important reasons.

PHYSICAL MODELING

Comprehensive quantitative models are an ultimate objective of solar research and an essential step toward practical use of our knowledge. At least seven kinds are needed: (1) hydrogen convection zone models that describe global circulation, oscillations, and, ultimately, the space and time dependence of the photon and nonradiative energy fluxes, and the magnetic field, leaving the top of the convection zone; (2) models that relate the evolution of strong magnetic fields in active regions to the production of energetic particles and photons in solar flares; (3) hydrodynamic models of the propagation of thermal flare plasma throughout the chromosphere, transition regions, and corona; (4) models of the nonradiative energy flux throughout the solar atmosphere; (5) models of the expansion of the corona from open magnetic field regions; (6) three-dimensional models of the time evolution of solar-wind structures throughout interplanetary space; (7) models of the interaction of solar and galactic cosmic rays with the interplanetary plasma and magnetic field. Microscopic plasma processes are essential parts of each model.

6
Magnetospheric Physics

BACKGROUND

Three multiple spacecraft Explorer missions and Spacelab 1 constitute NASA's recent or approved spaceflight program. The International Sun-Earth Explorers 1 and 2 (ISEE-1 and -2), by virtue of their closely spaced orbits, are making high-resolution measurements of the bow shock, magnetopause, and magnetosphere within 22 earth radii (R_e) geocentric distance, while ISEE-3 simultaneously studies the solar wind 235 R_e upstream of earth. One Dynamics Explorer (DE) spacecraft will study the field-aligned currents connecting the magnetosphere and ionosphere and image the aurora from high altitudes, while its companion will make complementary measurements at lower altitudes. The Active Magnetospheric Particle Tracer Explorer will inject identifiable ions into the solar wind and magnetosphere and trace their subsequent magnetospheric entry and transport using instruments on a companion spacecraft and on the ground. Spacelab 1 will permit first orbital uses of a facility to inject energetic electron beams into the midlatitude ionosphere and magnetosphere and of auroral television imaging.

Spacecraft operated by the Department of Defense, the National Oceanic and Atmospheric Administration, and other nations are making and will continue to make substantial contributions to magnetospheric physics, as are the space measurements coordinated with ground-based observation in the International Magnetospheric Study (IMS).

BALANCE BETWEEN GLOBAL AND INTENSIVE RESEARCH

This balance is dynamic. Because there are no remote-sensing techniques that reveal the magnetosphere's structure at a glance, synopsis of *in situ* measurements at different points in space is the only experimental way to deduce global magnetospheric behavior. Single spacecraft measurements are increasingly marginal since they do not reveal instantaneous spatial structure. On the other hand, without detailed study of the plasma processes occurring at certain crucial points, the global synopsis will be severely compromised.

FREE-FLYING SPACECRAFT

There is no quantitative model of magnetospheric dynamics. The time-dependent exchanges of energy and plasma between the solar wind and the magnetosphere, ionosphere, and atmosphere have not been measured sufficiently synoptically to test proposed models adequately. Our present understanding indicates that simultaneous plasma measurements at six critical regions are the next step needed to clarify and begin quantification of present magnetospheric models: (1) Recent measurements, from the Interplanetary Monitoring Platforms 7 and 8, among others, have revealed time-varying high-speed plasma flows that originate in the distant tail and deposit at least part of their energy and plasma in the atmosphere. Since spacecraft rarely have studied the tail beyond 60 R_e, our lack of information about this crucial region of space limits progress in many areas of magnetospheric physics. (2) Measurements well upstream of earth are essential to determine the time-variable solar-wind input to the magnetosphere. (3) Calculations of the total auroral energy deposition rate require multispectral imaging of auroral photons over the *entire* deposition region. Time resolution sufficient to follow substorm development and spatial resolution sufficient to discern auroral substructures are essential. Auroral imaging, together with further *in situ* plasma studies on magnetic field lines connecting to the aurora, requires a polar elliptical orbiter. (4) Studies of plasma composition, injection, storage, and loss in the inner magnetosphere and of dayside magnetopause transport require a roughly 2×15 R_e elliptical orbiter near the geomagnetic equatorial plane. (5) A low-altitude polar orbiter is needed to measure the dynamical and chemical response of the ionosphere and atmosphere to solar wind and magnetospheric variability. (6) Polar cap and auroral zone ground-based measurements provide information necessary to complete the calculation of the auroral energy budget.

We recommend that all six critical regions be investigated simultaneously for at least 1.5 years. While there conceivably may emerge several ways to do this, a unified project that provides matched instrumentation and planned data flow is the best way to provide the maximum scientific return. Therefore, four new spacecraft—in the solar wind, in the geotail, above the aurora, and in the midmagnetosphere—joined with an upper-atmospheric series polar orbiter and ground-based measurements—are the highest new priority for magnetospheric physics. A strong effort should be made to assure simultaneous measurements in the six regions. Thus, engineering, fiscal, and other trade-offs should be made across the entire project. Data should be collected and disseminated programwide. While a 1.5-year minimum time suits the upper-atmospheric spacecraft, the other spacecraft lifetimes should not be intentionally limited. An orbital adjust capability would greatly extend the range of problems that could be studied, by effectively creating several programs in place of one. If all four magnetospheric spacecraft could modify their orbits and live long enough, this one project could serve magnetospheric physics' major needs for many years.

SHUTTLE ACTIVE EXPERIMENTS

Active experiments, largely ground-based or rocketborne, are an increasing part of magnetospheric research. The Shuttle will make possible large active space experiments, including chemical, plasma, and wave injections used as nonperturbing tracers or controllable stimuli of measurable responses. Some, such as electron-beam injections, may be of direct magnetospheric interest; others, such as chemical releases, of ionospheric and atmospheric interest; some, such as gas, or electron-beam injections made in conjunction with remote atmospheric sensing to study interactions between drifting ionospheric plasma and neutral winds, may be of interest to both; still others, such as wave injections, may have plasma physical significance. In certain cases, subsatellites will be necessary to provide platforms free of electromagnetic or chemical contamination that observe at a distance the consequences of active experiments. Subsatellites can also make inexpensive multipoint measurements.

The Shuttle will advance a new space-science discipline—experimental plasma physics in space—whose research should be judged in part according to its plasma-physics interest. Experience indicates that space and laboratory plasmas behave differently in detail because of the sensitive parametric dependences of their nonlinear processes. Because it is difficult to reproduce space plasmas in the laboratory, questions will remain about their behavior unless experiments are actually performed in space. However, since laboratory experience can help design and interpret active experiments, members of the laboratory plasma community should participate in them.

By contrast with atmospheric and solar physics, where the importance of Shuttle high-resolution measurements is foreseeable, the impact of active experiments is difficult to predict, largely because many pioneering experiments are yet to be carried out. However, new experimental techniques often lead to basic knowledge of unforeseen character. *We recommend continued development of wave injections; electron, ion, and plasma injection; and* *chemical release facilities so that the objectives and pace of their subsequent systematic use may be better defined from the results of their first flights.*

Longer Shuttle flights could significantly improve active experiments. A seven-day flight severely limits the time to execute experiments. Two to four weeks in orbit could multiply considerably the actual time available to them. Many active experiments could use to advantage the increased power from a power module. Shuttle power and flight duration will be major factors determining the scientific potential of active experiments.

EXPLORERS

Although Explorers, such as ISEE, DE, and AMPTE, have been mainstays of magnetospheric research, it is increasingly difficult to meet our major objectives within the Explorer budget. However, Explorers are cost-effective, attractive candidates for Shuttle subsatellites and satellite clusters to make *in situ* measurements with high spatial resolution. Explorers could also study the plasma physics of the equatorial ionosphere or of the near geomagnetic tail, objectives not specifically addressed in this strategy.

ROCKETS, BALLOONS, AND GROUND-BASED FACILITIES

Polar-cap and auroral-zone radars, digital magnetometer chains, and other facilities provide information necessary to calculate the auroral energy budget. For example, radar measurements of plasma drifts and neutral wind speed are needed to determine the exchange of momentum between the magnetosphere, ionosphere, and atmosphere. Measurements of ionospheric currents and conductivity must be combined to calculate Joule dissipation, which contributes roughly as much as auroral particle deposition to the total dissipation rate.

The ability of rockets to make vertical-profile and low-altitude measurements has enabled them to lead research on structured auroral arcs. Balloons provide a stable platform to measure the electric field in the ionosphere and atmosphere. A balloon and rocket program should be maintained for these and other purposes.

INSTRUMENT DEVELOPMENT

It will be important to continue to create a flexible array of instruments for Shuttle use, since active experiments are just beginning. Multispectral auroral imaging systems, designed in conjunction with models that turn photon flux measurements into energy deposition calculations, need further development. Novel techniques for remote sensing of features throughout the magnetosphere should be encouraged. Recent theoretical and laboratory research suggests that turbulent plasmas develop small structures, on the Debye length space scale and plasma period time scale, which if not detected could limit our understanding of magnetospheric plasma turbulence. There is, therefore, a need for plasma and plasma-wave detectors that can record short bursts of activity without overburdening the general data stream.

It is a considerable effort to assemble even the most basic plasma diagnostics, since data from the different instruments on a given spacecraft are analyzed by separate groups; therefore, new designs and methods of selection of integrated plasma information systems, involving magnetic field, electric field, energetic particle, plasma and plasma-wave detectors, together with associated data-processing techniques, are needed.

QUANTITATIVE MODELS

Comprehensive quantitative models are one ultimate goal of magnetospheric research and an essential step toward practical use of our knowledge. At least five kinds are needed: (1) time-dependent hydromagnetic models of the interaction between the solar wind and magnetosphere; (2) models of the time-variable interaction between the magnetosphere, ionosphere, and atmosphere; (3) models of the plasma flow within the magnetosphere; (4) time-dependent models of the radiation belts and ring current and their losses to the atmosphere; and (5) models that relate auroral photons to magnetosphere plasma energy deposition. Numerical simulations of basic space-plasma processes, such as magnetic field reconnection, turbulent diffusion, and unstable magnetic field-aligned currents, will also be needed.

7
Upper-Atmospheric Physics

BACKGROUND

Highly interactive use of data from three Atmosphere Explorers decisively improved quantitative understanding of the photochemistry of the thermosphere above 130 km. Two Dynamics Explorers will study the interaction between the magnetosphere and atmosphere from both locations simultaneously for the first time. The Solar Mesosphere Explorer (SME) will make initial infrared measurements and survey the distribution and variability of ozone and NO_x in the stratosphere and mesosphere. Spacelab 1 will make preliminary measurements of upper-atmospheric winds, airglow, and infrared emissions.

Remote sensing of the middle atmosphere from space will assume special significance during the Middle Atmosphere Program (MAP), 1982–1985. MAP will be a major international program whose overall objective will be a coordinated, systematic attack on the unsolved problems of the middle atmosphere. Spacecraft with remote-sensing capabilities will form a vital U.S. contribution to MAP.

BALANCE BETWEEN GLOBAL AND INTENSIVE STUDIES

First priority must be given to global studies of atmospheric energy sources, composition, chemistry, and circulation, to improve understanding of the middle atmosphere, perceive possible links between solar activity and weather, and detect and monitor man-made perturbations. Reasonably continuous coverage is needed to study the solar-cycle dependence of the middle and upper atmosphere. These global studies should be supplemented by Shuttle-Spacelab measurements, albeit of short duration, that achieve higher spatial, temporal, or spectral resolution, as well as by ground-based and *in situ* measurements.

FREE-FLYING SPACECRAFT

Because cryogenic infrared detectors have limited lifetimes, and because one orbit does not provide global coverage, we cannot recommend one long mission but rather an evolutionary sequence of 1.5-year free-flying missions, Shuttle retrievable and refurbishable, coordinated in an upper-atmospheric research series. The first two in the series are well defined. A low-inclination spacecraft followed by a high-inclination orbiter is needed for good geographical and seasonal coverage. Their flights should overlap for six months to provide pole-to-equator coverage and validate instrument calibration. They should emphasize the radiant energy balance and chemistry of the stratosphere, mesosphere, and lower thermosphere. Studies of dynamics, transport, and interactions between atmospheric layers are also important. For missions following these two, an additional emphasis should be placed on the effects of magnetospheric motions, electric fields, and charged-particle precipitation on the polar ionosphere, thermosphere, and mesosphere. These could be studied using a low-altitude polar-orbiting element of the series or perhaps a spacecraft tethered to a Shuttle-launched platform. In either case, these studies should be concurrent with global ovservations of the aurora and polar caps from the atmosphere.

We recommend that spacecraft investigations of the upper atmosphere continue throughout the 1980's, to ensure adequate geographical, diurnal, seasonal, and solar-cycle coverage. We recommend that long-range planning, beginning with definition of a third element in the series, commence soon.

Radiative-balance climate models indicate that the earth's surface temperature could be sensitive to changes in the solar radiant energy flux as small as 0.1 percent. *For our understanding of the influence of solar variability on climate to progress beyond speculation, long-term satellite monitoring of the total solar radiant energy flux should take place. The solar spectral irradiance should also be monitored, emphasizing the ultraviolet part of the spectrum, which is known to vary with solar activity.*

SHUTTLE AND SOLAR-TERRESTRIAL OBSERVATORY

The Shuttle can orbit heavy instrumentation capable of important high spatial, temporal, and spectral resolution measurements. Instrument facilities, such as the laser version of radar (lidar) and the Cryogenic Limb-scanning Interferometer and Radiometer (CLIR), as well as smaller investigator-class instruments, can be developed with short-duration missions. However, to maximize their scientific return, Shuttle-class atmospheric instruments should be kept in space longer than one week.

Atmospheric measurements are a major objective of the Solar-Terrestrial Observatory (STO) to be discussed later. We recommend continued development of lidar and CLIR so they can ultimately be part of STO. Suitable PI-class instruments should also eventually become multi-user components of STO. In this way, a full complement of instruments to investigate such problems as energy flow and climate variation could be built up.

EXPLORERS

In the past, Explorers were quite important to atmospheric physics (viz., AE), and a Solar Mesosphere Explorer will be the first to study the middle atmosphere from space. Despite their stringent budget, Explorers can still help to develop new research areas. A study of atmospheric electrification is one example of a fruitful small-scale effort suitable for Explorers.

ROCKETS AND BALLOONS

A strong rocket and balloon program is needed to measure the ionic content, the concentrations of a number of minor species, the electrical state, and other properties of the middle atmosphere that cannot be observed remotely. The unique ability of rockets and balloons to measure small-scale phenomena is essential to further our understanding of middle-atmospheric transport processes; they can provide *in situ* corroboration of remote-sensing spacecraft observations and an inexpensive way to test new instruments. In addition, only rockets can make vertical profile measurements below 100-km altitude.

INSTRUMENT DEVELOPMENT

Remote measurements of upper-atmospheric motions would be a substantial step forward. *Instruments that can detect horizontal velocities of a few meters per second and vertical velocities considerably less than a meter per second should be developed.* Some, which measure horizontal velocities in the lower thermosphere and stratosphere by detecting Doppler shifts in visible and near-infrared emission or absorption lines, are being developed. Promising millimeter and microwave techniques should also be pursued. An advanced lidar with sensitivity sufficient to measure atmospheric motions could be a valuable part of a Solar-Terrestrial Observatory. Laser spectroscopy using multiple spacecraft is a concept worth supporting.

We recommend continued development of a spacecraft that can be tethered to the Shuttle or STO. This could allow simultaneous measurements of the ionosphere and atmosphere at several altitudes and controlled electrodynamic perturbations of the ionosphere.

PHYSICAL MODELING

One ultimate objective is a quantitative model that predicts the upper atmosphere's response to internal and external perturbations and describes how changes in it influence the lower atmosphere. Comprehensive models must take into account composition, radiation, and dynamics, because they are tightly coupled. In some areas, such as the radiation budget of those mesospheric regions not in local thermodynamic equilibrium, current models are primitive and a substantial preliminary effort will be required. In others, where adequate understanding of composition, radiation, and dynamics already exists, continuing interaction between model development and observation is the primary need.

Present general circulation models, which treat only the regions below an arbitrary upper boundary in the middle atmosphere, should be extended to the stratosphere, mesosphere, and thermosphere, so that they can also treat interactions between the upper and lower atmospheres.

8

Mission Scheduling; Evolution of Shuttle Science

Here we discuss issues important to solar-terrestrial physics as a whole.

MISSION COORDINATION

Judicious scheduling of the research proposed here could allow excellent coverage of the solar-terrestrial interaction. It could enable us to study together causally related events of the sun, in the heliosphere, and in the earth's space environment—one prerequisite to converting our largely phenomenological descriptions into quantitative models.

If multispacecraft measurements of the interaction between the solar wind and the earth, and global remote sensing from space of large-scale solar dynamics and solar flares, take place during the Solar Polar Mission (SPM), the heliospheric and terrestrial response to solar activity can be studied throughout the inner solar system. Moreover, the in-ecliptic solar-wind measurements made as part of the magnetospheric study and in-ecliptic solar observations complement the high-latitude SPM measurements in ways important to solar and heliospheric physics separately.

Combining a third polar orbiting element of the upper-atmospheric research series with the global magnetospheric study would provide new quantitative insight into how solar-wind-induced perturbations couple to upper-atmospheric winds and chemistry. To establish the basic information needed prior to studying magnetospheric coupling, the first two upper-atmospheric research satellites should be launched soon.

In situ solar measurements can probably be made only beyond several solar radii above the sun's surface, and possibly only beyond the solar wind's supersonic transition region. Simultaneous high-resolution observations of small-scale coronal structures and motions of the photosphere and chromosphere below the probe-flyby trajectory, will be needed to relate *in situ* measurements to surface phenomena and to study both sides of the solar wind's acceleration region. Therefore, coordinating a solar probe-flyby with a pinhole-coronagraph flight is synergistic. Since both are innovative technological undertakings, we cannot recommend a specific schedule for them. One factor affecting probe-flyby timing might be an increased potential hazard at the solar maximum, expected around 1990. If so, flying before this maximum would avoid a several-year delay in beginning *in situ* solar investigations.

Some Shuttle research has at present no defined linkage to other programs. However, the Solar Optical Telescope should be in use no later than 1984-1985 in order to study the ascent of the next solar maximum. Moreover, early first use of the Shuttle atmospheric and magnetospheric instruments enables early definition of systematic research using them. Coordinating research relating solar-terrestrial and lower-atmospheric phenomena is an important objective that we have not yet discussed. All of these issues are linked to the evolution of a Solar-Terrestrial Observatory, to which we next turn our attention.

SHUTTLE OPERATIONS

Achievement of polar orbital capability, long-duration use of Shuttle instruments, and a Solar-Terrestrial Observatory are related goals toward which Shuttle operations should evolve in the 1980's. Many important magnetospheric and atmospheric processes can only be studied from polar orbits; they are necessary to provide complete geographical coverage of the atmosphere and are excellent vantage points from which to view the sun. Lack of polar orbital capability would therefore seriously weaken the impact of the Shuttle on solar-terrestrial physics. We have already discussed the importance of long-duration use of Shuttle-class instruments to each of our subdisciplines. *We strongly recommend that the time in orbit of Shuttle-class instrumentation be extended.* Because of its impact on solar physics, the Solar Optical Telescope should be one of the first candidates for extended flight. *Furthermore, we recommend that present Shuttle instrument development be compatible with providing an eventual continuous presence in space of Shuttle-class solar-terrestrial instrumentation.*

A power module would permit at least two new modes of extended

Shuttle operation. A manned Shuttle spacecraft docked with a power module could remain in space much longer than seven days. Furthermore, several pallets of Shuttle-class instruments could remain attached to a free-flying unmanned power module to provide continuous observations for a year or more. The additional power would be important in itself; for example, because larger instruments could be cooled to lower temperatures, the sensitivity and resolution of infrared instruments would be increased. More power would increase lidar capabilities, bringing closer direct detection of atmospheric winds. Increased power available to plasma, energetic-particle, and wave-injection experiments extends the range of nonlinear plasma interactions that can be studied in space. Definition of new instruments that take advantage of the power module's unique capabilities should commence immediately.

Instruments currently being developed can be combined with a power module to create a free-flying Solar-Terrestrial Observatory whose capabilities will evolve as new instruments become available. While it cannot yet be precisely configured, some of its advantages seem clear. First, it can provide simultaneous long-duration high-resolution remote-sensing observations of the sun, atmosphere, and possibly magnetosphere, and facilitate their detailed intercomparison—for example, between solar spectral irradiance and upper-atmospheric variability. It could combine solar-terrestrial with lower-atmospheric measurements. It might make possible new investigations, such as resolved space measurements of upper-atmospheric winds and, perhaps, of tropospheric processes. There are advantages beyond increased payload, power, and flight duration. The ability to add or change instrument pallets means that one or at most a few modules could serve the changing needs of solar-terrestrial research and accommodate investigations sponsored by different NASA offices, governmental agencies, or nations. When desirable, man can be in the loop, either in space or on the ground, an interactive capability that proved useful in Skylab studies of the sun. Since modular construction imposes fewer weight and size constraints, an operational Solar-Terrestrial Observatory could well inspire use of instruments of capability hitherto impractical. All in all, it would be a major advance.

We recommend that studies defining a Solar-Terrestrial Observatory proceed with high priority. If operational by the mid-1980's, it could conceivably perform the functions of several free-flyers otherwise needed to achieve the objectives of this strategy.

9
Theory, Information, and Cooperative Research

THEORY

The Study Panel on Space Plasma Physics concluded that "theory [should] play a central role in the planned development of the field"; they also found that "the current level of theoretical effort is inadequate throughout solar system plasma physics. The degree of inadequacy varies from subject to subject, but inadequacy exists across the board." *We agree with these conclusions.*

The world effort to achieve controlled thermonuclear fusion and the discoveries of plasmas in space have stimulated a rapid development of plasma physics in the past two decades. Yet many plasma processes are poorly understood, largely because they are nonlinear and parameter sensitive. As a result, laboratory research sheds only partial light on space plasmas. Many practicing space experimentalists were not trained in plasma physics, which increases their dependence on theoreticians to interpret data. The urgency of the controlled thermonuclear fusion program means that the space-plasma community will have to develop its own theory.

The situation in theoretical upper-atmospheric physics is a happier one. For example, the need for comprehensive modeling was attended to earlier than in space-plasma physics. Nonetheless, while theoretical upper-atmospheric physics is adequate for its present tasks, its highly significant future opportunities outlined in this document justify a strengthened theoretical effort.

We understand that NASA may create a specific program for solar–terrestrial theory and analysis. We strongly endorse this program because several additional theoretical groups are urgently needed to create the increasingly quantitative theories required to motivate and interpret space observations and to create comprehensive models. These groups should be broadly concerned with all aspects of solar-system physics and especially plasma physics. Experimental groups should henceforth have theoretical capability sufficient to aid their data analysis, as well as to participate in creating theory. Numerical simulation has become a major tool used to understand laboratory, but not space, plasmas. As we have indicated, comprehensive models now are needed to advance many solar-terrestrial problems. Thus, systematic use of models and simulations should be initiated in solar-system plasma physics and strengthened in atmospheric physics.

Other activities that increase theoretical understanding should also be encouraged. Certain laboratory experiments can contribute to our knowledge of the upper atmosphere and space plasmas. Series of problem-oriented workshops, already helpful to solar physics, are an effective means to compare theory and observation. Interdisciplinary workshops linking solar-terrestrial research with meteorology and climatology and with astrophysics will stimulate new theoretical perceptions.

THE SOLAR-TERRESTRIAL PHYSICS INFORMATION CHAIN

The traditional disciplines of solar, heliospheric, magnetospheric, ionospheric, and atmospheric physics evolved from distinct origins along different but converging paths. As each moved beyond primitive phenomenology, it demanded increasingly quantitative measurements, such as high-resolution images and plasma distribution functions. Moreover, each required close integration of different measurements to assemble complete diagnostic information about events observed by individual spacecraft. Each has now developed its own sophisticated ways to convert data into knowledge at this first level of integration. Probing deeper, each discipline perceived its problems and regions of space to be linked to others. Multipoint data integration, exemplified by the three ISEE spacecraft, which are part of a larger International Magnetospheric Survey, is an immature art whose importance grows daily. A third level of integration will be needed for quantitative studies of solar activity, because different disciplines will have to work together. For example, remote sensing of the sun can estimate how much energy is released in a solar flare, widely spaced interplanetary spacecraft can reconstruct its propagation in the heliosphere, and magnetospheric and atmospheric spacecraft can determine how it interacts with earth. A fourth level of integration is required to deduce, from long time series of individual events, the effects on earth of the solar cycle and *its* variability. An equally complex meteorological and climatological information chain must be brought together with the solar-terrestrial one to advance sun-weather-climate research. Such fourth-level correlation studies have gone on for some time, often without the backing of quantitative information from the first three levels.

Allocation of informational resources is of fundamental importance to solar-terrestrial physics. *The many activities comprising its information chain–data acquisition, reduction, dissemination, correlation, analysis, storage, and retrieval–must rise to a higher level of sophistication to generate the increasingly quantitative information needed in solar-terrestrial research.* Since the goals ultimately motivating these activities are creation and use of quantitative knowledge, theory and modeling should play a primary role in guiding this evolution, and advances in technology, in speeding it. Objectives for the 1980's include reducing the time to assemble quantitative information from different instruments on board a single spacecraft, creating accessible problem-oriented data streams relating observations made at different points in space and on the ground and facilitating correlation of data from different disciplines. We recommend that NASA's solar-terrestrial information chains be reviewed and where necessary improved.

Besides the objectives above, we have also identified the following concerns. We are seriously concerned that insufficient data may be acquired, especially from spacecraft that cannot use the Tracking and Data Relay Satellite System (TDRSS) but also from those sharing TDRSS. The projected solar-terrestrial data-acquisition needs should be an early item for review. Data acquired from older spacecraft well after conclusion of their prime mission phase have proven their value time and again. Therefore, data acquisition from continuing as well as new missions should be provided for. Finally, archival procedures should encourage the active use of data from inactive spacecraft more than has been the case up to now.

We, together with the Study Group on Space Plasma Physics, find that current data-analysis funding is inadequate. As one step, we suggest that projects, where appropriate, find organizational means to extend their data-analysis responsibility beyond the currently normal two years.

COOPERATIVE RESEARCH

The solar-terrestrial information chain is open-ended. Contributions from the Department of Defense (DOD), NASA, the National Oceanic and Atmospheric Administration (NOAA), and international spacecraft and many ground facilities and observatories should enter it. It should be open to research and applications communities at large. NOAA sponsors an effort to assemble and disseminate such information to scientific, industrial, and governmental users. Despite limited resources, it plays a key role in coordinating the International Magnetospheric Study.

The objectives of future solar-terrestrial research provide the need, and its applications one reason, to broaden the nation's efforts to assemble and disseminate solar-terrestrial data. *We therefore recommend that these efforts be guided toward a national solar-terrestrial information system* that facilitates access to data of diverse origins and disciplines, promotes problem-oriented data use, contributes to physical modeling, and serves as a prototype for possible operational systems. A major definition study is needed.

The increasing importance of synoptic data acquisition has led each of our subdisciplines to cooperative research efforts—for example, the Solar Maximum Year, the Middle Atmosphere Program, and the International Magnetospheric Study. Yet there never has been one devoted to the entire solar-terrestrial interaction. 1986-1987, when many spacecraft stand watch during the polar passage of SPM, will be the first practical opportunity to do this. Experience suggests that coordination of the research sponsored by DOD, the Department of Energy, NASA, NOAA, the National Science Foundation, and possibly other nations will maximize this opportunity. We therefore urge that a decision be made soon whether this cooperative research will take place.

III
Problems of Solar-System Space Physics

10
Solar Physics

We start with the study of the sun itself. Its position as the star closest to earth gives it two important advantages. First, its outer regions, the corona and the solar wind, can be sampled *in situ*. Second, its surface can be observed much as terrestrial spacecraft view the earth's surface. Solar physics has much in common with terrestrial atmospheric, ionospheric, and magnetospheric physics–one example is the similarity between magnetospheric substorms and solar flares. On the other hand, the sun is far enough from earth that our viewpoint is naturally global. Much of what we know about the sun has been learned using remote-sensing techniques shared with astrophysics. In fact, many theoretical and observational tools used subsequently in astrophysics were first developed to study solar problems. This common heritage is important to both disciplines. Although our strategy is concerned with the solar-terrestrial context of solar physics, its astrophysical implications are important; for instance, the solar dynamo and flares are examples of basic astrophysical processes.

We will not repeat the excellent summary of important problems of solar physics given in *Report on Space Science 1975*. Here we concentrate on those that progressed most rapidly since that report and those that seem most relevant to solar-terrestrial physics. Four have been singled out on this basis, starting with the sun and moving out toward earth. First, the last decade saw dramatic developments in understanding global solar structure and in modeling of convection. These problems are avenues to understanding the generation of the solar magnetic field and solar activity. Second, considerable progress was made in understanding the effects, and less so the causes, of solar flares. Third, recent OSO-8 and ATM data have forced us to re-evaluate our ideas about the nonradiative energy flux in the entire solar atmosphere. Finally, we have recently realized that the large-scale, weak solar magnetic field determines how coronal and interplanetary hydromagnetic structures are interrelated.

SOLAR GLOBAL CIRCULATION

The solar dynamo problem lies at the heart of solar variability. Our present understanding of it is highly limited. We cannot directly observe the solar convection zone, the seat of the solar dynamo, but only its manifestations at and above the surface of the sun. Recent observation and theory have provided new insights into its behavior, including (a) observations of global oscillations of the sun that may indicate fundamental resonances of its interior; (b) new interpretations of short-period oscillations that permit inferences concerning the rotation gradient below the directly observable surface of the sun; and (c) sophisticated numerical models of the solar convection zone that are beginning to assess the global convection dynamo.

Until recently, most theories of global circulation started with the mean differential rotation profile with solar latitude as given and proceeded to explain its consequences. New models, focused on how solar rotation modifies convection to produce differential rotation, can account for the average differential rotation profile. In addition, they make several predictions concerning the interior of the convection zone. Examination of the dynamo action of global convection, which drives the differential rotation, is now possible, and the large-scale magnetic field, so calculated, can be compared to observations. A chain of inferences deducible from the observed properties of coronal holes does suggest that they are coupled to the solar interior by the large-scale magnetic field.

At present, the most important approach to the solar dynamo is through the study of the solar global circulation and its oscillations. Our rapidly developing theoretical understanding is making observations of the large-scale velocity field and global oscillations increasingly meaningful. Space observations can provide definitive information about global oscillations by removing interference of the terrestrial atmosphere, thereby resolving questions concerning ground observations. Space observations provide information on short-period phenomena and large-scale velocity field variations that is unobtainable from the ground.

Several small-scale phenomena in the solar convection zone could influence the strength and configuration of the surface magnetic fields and therefore of coronal holes and solar wind streams. These include hydromagnetic, rotational and dynamo waves, magnetic buoyancy, and—most probably—magnetic-field-line reconnection.

Little is known about possible variations in the total radiative output of the sun—the so-called "solar constant." Such variations if detected would have significant implications concerning solar structure and mechanisms of energy transport, as well as for terrestrial climate studies.

SOLAR FLARES AND HIGH-ENERGY PHENOMENA

Solar flares have a direct impact on earth. Energetic solar-flare protons are the main nonradiative solar output known thus far to affect directly the earth's lower atmosphere. Solar-flare plasma creates a magnetic storm when it envelops the earth. Solar flares accelerate particles to very high energy and probably involve magnetic-field-line reconnection. Both processes occur throughout the astrophysical universe and both have been identified by the study panel on space plasma physics as fundamental problems of plasma physics.

It appears that energy can be stored in current-carrying strong coronal magnetic field structures that are metastable prior to flare onset. The free energy of the magnetic field is explosively released—perhaps by reconnection —partly in the form of energetic electrons that produce bursts of microwave radiation and x rays when they hit the solar atmosphere below the flare site. This leads to an explosive evaporation of the chromosphere to produce a hot ($>10^7$ K) plasma, which in turn is responsible for subsequent soft x rays, enhanced chronospheric radiation, and, possibly, a blast wave. Finally, the corona surrounding the flare site is filled with hot plasma, which maintains the decay phase of the flare for hours or days.

Not only can flare acceleration of energetic particles be inferred from observations of hard x rays and radio bursts, but the fluxes, spectra, and composition of those particles released into the interplanetary medium can be measured directly. X-ray and gamma-ray flare observations provide information on the energetic protons and nuclei at or near the site of their acceleration. Although no solar neutron flux has been detected unambiguously, it is likely that the sun generates neutrons near the photosphere and the flare site. Observations of rare isotopes, such as ^{3}He, provide information about the composition of the substrate plasma prior to the flare and, possibly, the plasma and nuclear physics of the flare site itself.

Some outstanding questions concerning flares are: What is the spatial configuration and strength of the electric and magnetic fields at and surrounding the flare site prior to flare onset, during the explosive phase, and in the recovery phase? How, where, and when are particles accelerated to high energies? What is the role played by microscopic plasma processes in the flare explosion, and in accelerating particles? The operational International Sun-Earth Explorer mission (ISEE) and the approved Solar Maximum Mission

(SMM) will provide important clues needed to answer these questions. Finally, the approved Solar Polar Mission (SPM), if supplemented with by in-ecliptic measurements, would provide important three-dimensional data relating to the solid angle of shock energetic particle propagation, preflare loop structures, and flare-associated coronal transient events.

The explosive phase of solar flares is the least well understood. Because of weight and volume limitations, SMM will not provide sufficient spatial and temporal resolution to study definitively the flare site, which is thought to be very small; further progress in understanding solar flares requires higher-spatial-resolution optical, hard x-ray, and gamma-ray measurements.

THE NONRADIATIVE ENERGY FLUX

The nonradiative energy flux emanating from the top of the convection zone in such forms as mechanical waves and electron heat flux is largely dissipated in the chromosphere, providing most of the energy appearing as line emission in the solar electromagnetic spectrum. The remainder of the flux heats the corona and drives the solar wind. Its basic character is not understood. Until recently, it was thought that it was carried primarily by waves, but OSO-8 spectral observations of the chromosphere place a low upper limit on the mechanical wave flux propagating into the upper chromosphere and corona. Interpretation of the OSO-8 data was compromised by its limited spatial resolution. Future progress requires resolution better than 1 arc sec, together with the ability to cover areas of supergranular dimensions in times that are a small fraction of the period of waves important to chromospheric or coronal heating. Extension of these capabilities below Lyman-α into the EUV wavelength region opens the exciting possibility of tracing the transient dissipation of the energy flux from the chromosphere through the solar-wind critical layer into the corona. This problem would also benefit from further theory on the propagation of waves through the chromosphere, transition region, and corona.

LARGE-SCALE WEAK MAGNETIC FIELD

The large-scale weak magnetic field and its variations involve major unsolved problems of solar physics. This field, a consequence of global solar convection, organizes all coronal structures; these play significant roles in determining the mass, momentum, and energy flux delivered to the heliosphere by the solar wind. *Observations of coronal structures are best carried out from space.* Those recently obtained on Skylab, together with interplanetary observations and indirect inferences drawn from the variation of terrestrial magnetic activity indices, indicate that coronal and solar-wind structures are stable over several solar rotations near solar minimum but are unstable during the ascending phase of the solar cycle. Therefore, to determine their evolution from one configuration to the next, remote observations of large-scale coronal magnetic fields should be made over several solar rotations and at different phases of the solar cycle.

THE SOLAR WIND AND HELIOSPHERE

Activity at the solar surface sets the stage for the generation of the solar wind by providing a complex variable magnetic topology from which the heated solar corona escapes into interplanetary space. That part of the corona not confined by the large-scale solar magnetic field expands in a flow that is subsonic near the sun and supersonic throughout interplanetary space. This flow transports plasma, energy, angular momentum, and magnetic field past all the planets. It is finally decelerated to subsonic speeds by its interaction with interstellar matter at a distance of a few hundred astronomical units. The heliosphere is the region of flow of solar origin; its boundary, the heliopause, separates the solar wind and interstellar plasma.

Expanding hydromagnetic flows like the solar wind are common in astrophysics. The plasma in globular clusters and galactic halos may expand in similar fashion. Relativistic winds have been proposed for pulsars and radio galaxies. Stars like the sun that have convective outer layers are inferred to have stellar winds. The solar wind has carried off much of the sun's original angular momentum over the sun's lifetime; other stars that have convective outer layers are observed to rotate slowly like the sun does. More massive stars are observed to have stellar winds driven by radiation pressure. The solar wind is the only one accessible to *in situ* measurement. Consequently, it is the only one for which measurements of the microscopic plasma processes that regulate transport and accelerate particles are possible.

Since 1961, the solar-wind flow speed, density, temperature, chemical composition, ionization state, and magnetic field have been studied in great detail near the earth. In the past five years, ecliptic-plane solar-wind measurements have been extended to within the orbit of Mercury and near the orbit of Saturn. Four recent achievements in solar-wind research stand out. First is the development of models describing the temporal and spatial evolution of large-scale solar-wind structures, including high-speed solar-wind streams, and flare-produced shock waves. Next, the realization that high-speed solar-wind streams, and possibly much of the low-speed solar wind, originate in the low-density rapidly diverging magnetic flux tubes of coronal holes has re-oriented much solar-wind research. Third, the sector structure of the solar wind has been related to a magnetic neutral sheet of solar-system scale connected to the large-scale magnetic field of the rotating sun. Finally, important progress has been made in understanding how microscopic plasma processes regulate solar-wind transport.

We have identified three major objectives for solar wind research in the 1980's: to understand how the solar wind is generated, how it behaves in three dimensions, and its microscopic plasma physics.

SOLAR-WIND GENERATION

Here one must study the critical layer within a new solar radii of the sun's surface, where the plasma energy that flows into the corona from below is transformed into the energy of the outflowing solar wind. This requires consideration of (a) the three-dimensional structure of the coronal magnetic field; (b) the nature and magnitude of the wave energy flux entering the corona from the lower atmosphere and its conversion into flow energy; (c) the physics of the coronal electron heat flux when it is regulated by microscopic plasma processes rather than by collisions.

Three-dimensional information about coronal magnetic fields can be obtained in two ways. The approved Solar Polar Mission, if supplemented by observations in the ecliptic plane, can provide a stereoscopic global view at several wavelengths of the magnetic structures below the solar-wind critical layer. Second, direct *in situ* measurements of the local magnetic field can be made along the trajectory of a spacecraft that passes near the critical region. Such measurements of the magnetic field can also reveal small magnetic features unresolvable by remote sensing.

In situ measurements can provide information about solar-wind generation obtainable in no other way, for example, the density, temperature, and speed of the solar wind where it is still being accelerated. They make it possible to measure the time-dependent energetic particle spectrum in the solar corona. We have no definitive experimental information on microscopic coronal processes, including those determining electron heat fluxes and those involved in magnetic field reconnection, and particle acceleration. *In situ* measurements are necessary to put our understanding of them on firmer ground. *In situ* measurements, which provide accurate information at a single point in space, should be complemented by remote sensing. A spacecraft passing close to the sun can observe the lower corona with a resolution greater than that possible from earth orbit.

The energy flux entering the corona from below should be studied using chromospheric observations with better areal coverage and spatial resolution than on OSO-8. Indirect measurements down to the coronal base may come from spectral observations of Lyman-α and other coronal lines, using an earth-orbiting coronagraph of high angular resolution, as well as by radio scintillation observations. These measurements, which pertain largely to regions below the critical layer, should be complemented by *in situ* measurements as close to the critical layer as possible.

THREE-DIMENSIONAL SOLAR-WIND STRUCTURE

Solar-wind structures, such as high-speed streams, interplanetary magnetic sectors, and flare-produced interplanetary shocks, are well understood only near the ecliptic plane. Their behavior out of the ecliptic is an open question. At present, our understanding of how solar wind transports angular momentum—central to the general stellar spindown problem—is severely limited by lack of precise measurements near the ecliptic plane and any measurements at all out of the ecliptic. The Solar Polar Mission should dramatically advance these problems, particularly if it is supplemented by simultaneous measurements in the ecliptic.

SOLAR-WIND PLASMA PROCESSES

This topic may be divided into two: the processes regulating transport in the solar wind, and to some extent the evolution of its structures, and those responsible for the acceleration and/or transport of energetic particles. Both are central to solar-wind research, and both have general plasma and astrophysical significance.

Near 1 A.U., the solar-wind electron heat flux appears at times to be limited by the unstable growth of microscopic plasma waves to a turbulent state. The relative speeds of ion beams in interpenetrating solar-wind streams may also be limited to below the local Alfvén speed by the unstable growth plasma waves. Interplanetary radio emissions, similar to Type III solar radio bursts, are excited by 5-100 keV solar electron streams. Hydromagnetic waves are generated at or near the sun, possibly play a major role in heating and accelerating the solar wind, couple minor ions to the main proton expansion, and transport significant energy and momentum. The solar wind is an excellent, and to date the primary, laboratory in which nonlinear hydromagnetic wave turbulence has been studied *in situ.*

Acceleration of particles to high energy occurs in laboratory, solar system, and astrophysical plasmas. The energetic particles observed in the solar wind may have accelerated at the sun, in planetary magnetospheres such as Jupiter's, or locally in the interplanetary medium, while those with energies exceeding several MeV/nucleon may have diffused into the heliosphere from interstellar space. We need to know whether those energetic particles with energies between 1 keV/nucleon and several MeV/nucleon are accelerated directly out of the solar-wind plasma, or whether they are first injected as energetic particles and then undergo further postacceleration in the interplanetary medium. Since the ionization states of solar wind and more energetic solar particles may differ, measurement of ionization state may determine particle origin. Particles are observed to be locally accelerated by interplanetary shock waves, a process of general astrophysical significance. Since present shock models suggest that they may be preferentially accelerated perpendicular to the ecliptic, measurements above the ecliptic plane may reveal larger fluxes than have been found thus far in the ecliptic plane.

Cosmic rays of galactic origin yield indirect information about the large-scale structure of the heliosphere and its variability with solar activity and the solar cycle. Although the question of stellar nucleosynthesis of galactic cosmic rays lies outside solar-system space physics, the study of interplanetary modulation of galactic cosmic rays definitely belongs and is also important to relate to atmospheric effects of cosmic rays, such as the tropospheric production of ^{14}C, modification of the fair-weather electric field, and stratospheric production of NO_x.

Macroscopic descriptions of cosmic-ray transport, in which cosmic-ray interactions with interplanetary magnetic turbulence are described by a phenomenologically determined diffusion tensor, have existed for some time. However, attempts to determine the diffusion tensor—indeed, to justify the diffusion approximation—from observations of solar-wind turbulence have met with limited success. Moreover, modulation theories suffer from poor understanding of the *three-dimensional* structure of the interplanetary medium. Hence, the most important measurements needed at present are of the energy spectrum at high heliographic latitudes. In addition, synoptic observations of the energy spectrum in the ecliptic plane are needed to study long-term variations of the modulation process. With such observations, the development of three-dimensional models of the interaction of galactic cosmic rays with the heliosphere should progress more rapidly.

INTERACTION OF THE SOLAR WIND WITH THE INTERSTELLAR MEDIUM

Interaction of galactic cosmic rays with the solar wind is but one facet of the interactions of the heliosphere with the surrounding interstellar medium. Interstellar neutrals are thought to penetrate deep into the heliosphere before they are ionized. Observations of the interplanetary neutral gas, which can be obtained indirectly from backscattered solar HI (1216 Å) and He I (584 Å) radiation, yield information about the local interstellar medium, global aspects of the three-dimensional structure of the heliosphere, and fire variability of the solar wind and solar radiation field. Neither the heliosphere boundary, the heliopause, nor the associated shock transition terminating supersonic solar wind flow, which lies within the heliopause, has been observed or quantitatively modeled. Observations of the shock and heliopause are obtainable from spacecraft passing out of the solar system, provided they function long enough. Because of the current transition to orbiter missions, the opportunities to encounter the interstellar medium following a planetary flyby may diminish in the future. A specific mission may eventually prove necessary.

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Magnetospheric and Ionospheric Physics

Earth's is the best understood of all magnetospheres. During the past two decades, magnetospheric research passed through successful stages of discovery and exploration, during which it identified, described phenomenologically, and began to understand many processes regulating earth's interaction with the solar wind. In so doing, it learned to use many research tools, including spacecraft, rocket, aircraft, and ground-based measurements, which, together with theory, must now be devoted to its next objective: *comprehensive quantitative understanding of the cause-and-effect relations between time-dependent magnetospheric processes.* This may be divided further into four basic tasks.

Since the magnetosphere acts like a blunt body standing in the supersonic solar wind, a collisionless bow shock stands upstream of it. The magnetopause is the boundary surface enclosing the magnetosphere cavity; the magnetosheath is the region between the magnetopause and bow shock containing shock-heated flowing plasma. Magnetosheath energy, momentum, plasma, magnetic and electric flux, and electric currents are coupled to the magnetosphere at rates set by microscopic plasma processes in the thin magnetopause. One task is to determine these magnetopause transport processes, how they vary when the upstream solar wind changes, and the global response of the magnetosphere to variation in magnetopause transport. The magnetosphere's time dependences should therefore be studied simultaneously with those of the solar wind.

The solar wind stretches the earth's magnetic field into a long magnetic tail, extending perhaps 1000 R_e downstream, which is separated into northern and southern lobes of opposite polarity by a sheet of hot plasma. The tail and plasma sheet are the site of the magnetospheric substorm—in which accumulated magnetic energy is explosively converted to plasma energy—with a host of consequences, such as enhanced auroral particle precipitation, light emission and ionospheric activity, injection of ions and electrons into the inner magnetosphere, and acceleration of particles to high energies in the tail. Although substorms are clearly the magnetosphere's fundamental mode of energy dissipation, many questions about them are not settled even conceptually, much less quantitatively. Do substorms depend on the immediate past history of the magnetosphere? Do they respond directly to solar-wind variability, or can they be internally triggered? Where in the tail does the explosion begin? Answers to this last question currently range from near the earth to beyond the moon's orbit. An indirect view of the distant tail has been obtained from observations of the earth's polar cap and auroral regions, since their magnetic fields connect to the tail. Recent satellite photographs have revealed auroral signatures of substorms occurring deeper in the tail than spacecraft normally penetrate.

Determining energy storage and release mechanisms in the earth's magnetic tail requires *in situ* measurements of the magnetic fields, plasma, plasma turbulence, and energetic particles within and beyond the orbit of the moon, global surveillance of auroral energy deposition, and knowledge of the simultaneous behavior of the solar wind.

Another task is determination of the origin and fate of the plasma in the magnetosphere. Some solar-wind plasma flows down field lines into the dayside ionosphere at high magnetic latitudes; some flows tailward in a thin boundary layer next to the magnetopause over the earth's magnetic poles. No spacecraft has been deep enough in the magnetic tail to permit observation of the expected closure across the tail of this solar-wind entry layer. Cool plasma of ionospheric origin expands into space. On low-latitude magnetic field lines, it fills the tubes of force until pressure equilibrium with the ionosphere is reached, creating a relatively dense "plasmasphere." On high-latitude open field lines, light ionospheric ions escape supersonically to the tail and ultimately to the solar wind in a miniature version of the solar wind—the polar wind. Recent observations of 1-5 keV O^+, He^+, and H^+ ions apparently accelerated in and then streaming upward from the aurora suggest that auroral processes provide a new source of energetic plasma for the magnetopause, whose importance—while undoubtedly great—has not yet been evaluated.

Determining the origin of magnetospheric plasmas requires time-resolved measurements of the spatial and velocity distributions, composition, and ionization state of the plasmas in the solar-wind entry layer, over the earth's polar caps and auroral regions and in the earth's magnetic tail. Understanding the fate of magnetospheric plasma requires not only measurements over the polar caps and auroral regions but also in the distant magnetosheath and the deep tail, where an inventory of the ions processed in the magnetosphere and escaping into the solar wind has yet to be made.

Although studies of earth's upper atmosphere, ionosphere, and magnetosphere developed separately, we now know that their separate names obscure the fact that the neutral and ionized gases above the tropopause respond sensitively in a mutually interconnected fashion to changes in earth's solar-system environment. Therefore, we should plan and execute our research on them in a way that reflects and reveals their interrelationship.

Our final task is to determine how the magnetosphere, ionosphere, and atmosphere interact and thereby influence each other's time-dependent behavior. This has been called electrodynamic coupling. How do the flows in the magnetosphere and the ionosphere-atmosphere, each of which produces an electric field, influence each other? They are coupled in part by electrical currents that flow along magnetic field lines connecting them. New measurements of electric fields and currents on a global scale illustrate just how dynamic the interchanges between magnetosphere and ionosphere-atmosphere are.

There remain two serious impediments to full understanding of electrodynamic coupling. The role of upper-atmospheric winds, while important, remains uncertain. By their interaction with the partially conducting ionosphere, thermospheric winds can generate, or be generated by, magnetospheric motion and heat input. Second, the physics of the electrical currents parallel to auroral magnetic field lines needs further clarification. Observations of high-altitude electric fields, and of energetic electrons and ions accelerated parallel to auroral field lines, suggest that large parallel electric currents create "anomalous" electric fields associated with strong plasma turbulence in shocklike layers at altitudes of several thousand kilometers. These layers also produce intense 100-kHz to 1-MHz radio noise. Evidence is accumulating that the energetic electron beams so accelerated produce the long striated arcs of the aurora when they impact the denser atmosphere at thermospheric (110-km) altitudes.

The closed chain of cause-and-effect relationships, involving magnetic-field-aligned currents, electric fields, ionospheric and magnetospheric plasmas, and atmospheric winds must be understood quantitatively and self-consistently. Spacecraft that directly measure plasma properties in the field-aligned current region, while simultaneously monitoring—together with ground-based diagnostics—the atmosphere and ionosphere below it are necessary. The interactions between the many variables above make electrodynamic coupling susceptible to, and needful of, numerical modeling. Finally, active experiments that break into the causal chain by introducing known perturbations and detecting nature's response will be valuable.

Electric fields are present at all height levels of the atmosphere. Magnetosphere fields penetrate to the stratosphere and perturb the global atmospheric electric potential. This downward mapping of electric fields is one clear, almost instantaneous coupling mechanism between upper- and lower-atmospheric processes. Quantitative upward mapping of fair weather and thunderstorm-related electric fields has recently begun. With the possible exception of mesospheric electric fields, measurement techniques are well developed, and a unified model of terrestrial electrodynamics is a realizable goal.

Since the ionosphere and magnetosphere are directly coupled at polar latitudes, it makes little sense to separate them conceptually. On the other hand, since the equatorial ionosphere is freer of direct magnetospheric influence, the plasma processes in its E and F regions differ from those at auroral latitudes. However, since the equatorial ionosphere still responds indirectly to changes in the electric field and winds caused by magnetospheric and interplanetary disturbances, it should be included in solar-terrestrial physics. Explorer-class spacecraft and continued rocket and radar research are needed to study it.

Each major task of magnetospheric physics has a plasma-physical component. The coupling between the magnetosheath and the magnetosphere is thought to be due either to magnetic-field-line reconnection or to turbulent plasma viscosity or a combination, at and near the magnetopause. Magnetic field reconnection is also a popular candidate for the substorm explosive energy release mechanism. Understanding the magnetospheric plasma sources involves understanding turbulent diffusion at the magnetospheric and particle acceleration in the aurora. The coupling of magnetospheric and ionospheric-atmospheric motions involves field-aligned currents that are unstable to the growth of both electrostatic and electromagnetic plasma waves.

To diagnose the magnetospheric plasma, we need to measure velocity and angular distributions of hydrogen, helium, oxygen, and perhaps heavier ions and electrons from below 10 eV to above 100 keV energy, quasi-dc magnetic and electric fields, and electromagnetic and electrostatic waves from below the local ion cyclotron frequency to above twice the local electron plasma and cyclotron frequencies. Detectors of each type have been flown on previous magnetospheric spacecraft. Their requirements depend on their objectives. For example, solar-wind studies require modest temporal resolution but high sensitivity to low particle fluxes, whereas studies on auroral field lines require high-time-resolution plasma measurements. However, future progress will depend equally on combining them in integrated problem-oriented complements of plasma detectors. For example, the instrumentation for the global magnetospheric study should be designed to provide, first, a set of commensurate data suitable for diagnosis of the magnetospheric large-scale behavior and, second, integrated data pertinent to the plasma process specific to each separate region of space.

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Upper-Atmospheric Physics

The upper atmosphere—that is, the neutral and ionized gases above the highest tropospheric clouds—is where solar-ultraviolet radiation is absorbed. It is the primary UV screen that protects biological life on earth. It is also the link between the convecting, electrically active magnetosphere and the lower atmosphere. The global thunderstorm electric curcuit is closed within the upper atmosphere.

The upper atmosphere has traditionally been divided into layers, which are, in order of increasing altitude, the stratosphere, mesosphere, thermosphere and ionosphere, and exosphere. Its higher regions, the thermosphere and ionosphere have been studied the most, since they are accessible to spacecraft. Early research concentrated on the highly nonthermal chemical processes resulting from absorption of hard ultraviolet solar radiation and energetic particles from the magnetosphere. The three Atmosphere Explorer satellites, which in large part quantified the chemistry above 130 km, are a culmination of the photochemical study of the thermosphere and ionosphere. One other outcome of the Atmosphere Explorer study has been a recognition that dynamical processes are much more important than previously thought—the realization of the strength of the coupling between the thermosphere and magnetosphere through driven convection motion of the ionosphere. Further studies of this coupling will be undertaken by the two Dynamic Explorer satellites in 1981.

Recent studies have shown that odd-nitrogen compounds play an important role in the thermosphere; moreover, they may well provide a direct source of odd nitrogen to the mesosphere. Thus, our present understanding of the ionosphere and thermosphere leads to new questions about their dynamics and to the recognition that transport from the thermosphere into the mesosphere is not well understood but may be important.

The possibility that chemicals produced by man may modify the atmosphere has intensified studies of stratospheric chemistry. Stratospheric absorption of the middle-ultraviolet regions of the solar spectrum generates odd-oxygen compounds of which the most important is ozone—the primary screen removing solar photons in the critical spectral region between 2000 and 3000 Å. The recognition that catalytic reactions between ozone and odd-nitrogen and odd-chlorine compounds rapidly destroy ozone has also profoundly influenced studies of the stratosphere. Again, the importance of coupling between what was thought to be two separate zones within the atmosphere has emerged. Transport and, indeed, stratospheric dynamics have been shown to be at best ill understood. The observed injection of odd-nitrogen compounds at high latitude during large solar proton events has emphasized the importance of heliospheric and magnetospheric coupling to even possibly the stratosphere.

The interchanges between the upper atmosphere and the troposphere cannot be fully understood without a considerable improvement in our primitive understanding of the mesosphere. The Solar Mesosphere Explorer will make initial remote-sensing studies of the distribution of ozone and odd-nitrogen compound in the mesosphere and upper stratosphere in recognition of the need for quantitative understanding of mesospheric chemistry.

It has become clear that the upper atmosphere is a chemically active region within which dynamics and transport act to couple all its layers together; it seems evident that the upper atmosphere is influenced by the troposphere and possibly could turn influence tropospheric climate and maybe weather. Variations of stratospheric chemical content influence ozone and, as a consequence, conditions at the surface of the earth. Variations of the conductivity of the stratosphere and mesosphere associated with cosmic-ray activity affect the fair-weather electric field and may influence thunderstorm growth. Thus, understanding ionic as well as neutral chemistry in the upper atmosphere is important.

The linkages between atmospheric layers extend beyond, to the sun itself, because changes in the solar-ultraviolet spectrum, and in the solar wind, modify primary processes within the upper atmosphere. Changes in the solar-photon spectrum lead to coupled chemical and dynamical perturbations. Changes in the solar wind are felt through variations in magnetospheric convection and auroral particles bombardment. Cosmic-ray ionization, which is modulated by the solar wind, influences the electrical state of the atmosphere. Our largely phenomenological knowledge of these processes needs to be made more quantitative.

In sum, we need information about the entire upper atmosphere, with good coverage of its geographical diurnal, seasonal, and solar-cycle dependences so that our understanding of the interrelationships discussed above, and others that we have not yet perceived, may be strengthened.

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Solar-Terrestrial Interactions

There is a more subtle "solar-terrestrial" connection between sun and earth beside the obvious one provided by sunlight reaching the ground. Our studies have begun to reveal a chain of processes that link variable phenomena near the surface of the sun to the magnetospheres, ionospheres, and atmospheres of the earth and other planets. The interactions between sun and earth that we have perceived thus far span the range of time scales from a few hours to the age of the solar system.

The earth's magnetosphere is kept in a constant state of agitation, because the solar wind is turbulent. Solar-wind fluctuations–particularly of magnetic field direction–can induce substorms–lasting a few hours, that enhance energetic particle deposition, ionospheric plasma production, and winds in the high-latitude thermosphere.

The first evidence that a large solar flare might occur is the appearance of a complex sunspot group in the sun's photosphere. Prompt electromagnetic radiation arrives at earth a few minutes after the energy in the coronal magnetic fields associated with the sunspot group is explosively released. Energetic solar-flare protons are guided by the interplanetary and geomagnetic field into the polar atmosphere soon afterward. The enhanced ionospheric plasma that they produce attenuates the radio noise received from cosmic radio sources. A day or so later, a shock wave passes over earth, enveloping it in dense, strongly magnetized, hot solar-flare plasma that compresses its magnetosphere. Substorms increase in frequency and intensity and inject hot plasma into the earth's inner magnetosphere to form a "ring current," which creates the geomagnetic field depression and activity that first motivated the name magnetic storm. Auroral particle precipitation and light production intensify and move to lower geomagnetic latitudes, creating a dense highly disturbed ionospheric plasma that interferes with radio communication and on occasion blacks it out altogether. Intense thermospheric wind systems, sometimes of a worldwide scale, are generated during magnetic storms.

Ionizing radiation of solar and magnetospheric origin can alter the chemical composition of the atmosphere by dissociating nitrogen, oxygen, and hydrogen compounds. The highly reactive species so produced can enter into catalytic cycles such as those involving odd-nitrogen compounds (NO_x) and ozone. Since NO_x has a long photochemical lifetime in the stratosphere, solar-magnetospheric ionizing radiation may significantly influence the ozone content of the atmosphere, principally at high latitudes but also—to a lesser extent—at all latitudes. Since the photochemical lifetime of NO is long at high latitudes in local winter, aurorally produced NO might diffuse vertically to lower altitudes—particularly during stratospheric warmings when sizable vertical wind velocities are expected.

The earth's atmosphere, ionosphere, and magnetosphere respond to changes in large-scale solar-wind structures that rotate with the sun. The polarity of the solar-wind magnetic field reverses abruptly from above to below a magnetic neutral sheet that lies near the ecliptic plane. This neutral sheet has a number of folds in it determined by how the solar-wind magnetic field happens to connect the weak large-scale solar field. Each time the folded neutral sheet passes over earth, the earth finds itself in a sector of reversed polarity. Since sector structure persists for several solar rotations, sector crossings tend to recur every 27 days (the solar rotation period), leading to a 27-day periodicity in various geomagnetic activity indices.

The number, position, and size of sunspots; the number and strength of solar flares and magnetic storms; and the large-scale solar and solar-wind magnetic fields are all modulated at the 11-13 year period of the solar cycle. So also are the galactic cosmic rays that penetrate the heliosphere far enough to reach the earth; they are most intense at solar minimum. The earth's upper atmosphere is hottest and densest at solar maximum, a fact important to calculations of spacecraft orbits.

No two solar cycles have been identical in the few hundred years of observation to date. Recent historical research has shown that solar activity can even be depressed for decades. Sunspots, first observed telescopically by Galileo in 1612, continued to be observed until 1645. They are absent in the historical record between 1645 and 1715. There is confirming evidence for increased ^{14}C production in the earth's upper atmosphere, consistent with enhanced ^{14}C production by galactic cosmic rays expected during periods of low solar activity. There is weaker ^{14}C evidence for depressed activity in the fifteenth century A.D. and in the fourth, seventh, and fourteenth centuries B.C. It has been determined recently that solar activity has either been abnormally high or abnormally low in 18 of the last 70 centuries and that the mean annual temperature in the north temperate zone has tended to track the level of solar activity through the 18 peaks and valleys. This raises the important question of how variations in solar activity on the time scale of centuries might affect the earth's climate.

Variations in the earth's magnetic field come into play on a still longer time scale. Every few hundred thousand years, the geomagnetic field changes polarity. When the field is very small, the earth's magnetosphere has a radically different structure. Since the area accessible to energetic particle deposition and auroral activity is then much larger, the effects of solar activity noticed during the present time of a normally large geomagnetic field should be very pronounced during geomagnetic field reversals. These effects last a small fraction of the field reversal cycle but many solar cycles. Since their maximum impact might come from the strongest solar cycle or from the strongest flares during the reversal, continued study of present extremes of solar activity is important. Since field reversals appear frequently in the geological record, they may be important to evaluation of the long-term effects of the solar wind on the earth.

The solar wind has varied over the age of the solar system. It was probably considerably more intense in the distant past, a fact indirectly corroborated by observation of the dependence of the rotation rate on the age of other stars with convective outer layers and, presumably, stellar winds. This may eventually impact our understanding of the evolution of the magnetospheres and atmospheres of the earth and planets.

14 Comparative Planetary Studies

Since we naturally do not understand other planets as well as earth, studies of each individual planet must continue to be important for the foreseeable future. Nonetheless, to increase their impact on solar-terrestrial physics we should seek *comparative* understanding of the interaction of the sun and solar wind with planets and comets. Comparative studies highlight the physics pertinent to each planet and put that of earth in a broad scientific context. Since much of the solar-terrestrial community also works actively in planetary research, advances in one area are rapidly communicated and applied to the other, so that comparative studies will naturally emerge provided that planning and data analysis in each are coordinated.

JUPITER'S MAGNETOSPHERE

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

Jupiter's outer magnetosphere is radially stretched into a highly time-variable dislike configuration completely different from earth's outer magnetosphere. It is modulated at Jupiter's 10-hour rotation period and, in addition, changes drastically on time scales of a few days to a week. Jupiter's magnetosphere generates—or permits to escape—such intense fluxes of relativistic electrons that Jupiter is the dominant source of 1-30 MeV cosmic-ray electrons in the heliosphere. Jupiter's satellite, Io, absorbs some radiation-belt particles and accelerates others; Io modulates the Jovian decametric radio emissions; and, most importantly, Io is a source of neutral atoms and a heavy-ion plasma that significantly affects the structure of Jupiter's magnetosphere.

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

While the four fundamental questions of magnetospheric physics posed in Chapter 3 for earth pertain to Jupiter as well, their answers are not so well understood in Jupiter's case. Since Jupiter's magnetopause is more structured and time-variable than earth's, how Jupiter's magnetosphere interacts with the solar wind is less well understood. Quantitative theories of Jupiter's three plasma sources—ionosphere, Io, and solar wind—are at present very rough. Atmospheric-ionospheric-magnetospheric interactions are important at Jupiter. Turbulent winds in Jupiter's upper atmosphere are thought to couple to turbulent hydromagnetic motions in its magnetosphere. This process may diffuse energetic particles inward to its radiation belts and low-energy plasma of Io and of ionospheric origin outward into its outer magnetosphere. However, even the basic structure of Jupiter's polar cap and auroral ionosphere is poorly understood.

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

THE MAGNETOSPHERE OF MERCURY

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

The four magnetosphere questions posed for earth and Jupiter will have different answers for Mercury. Because Mercury is closer to the sun, the solar-wind plasma energy flux and magnetic field are stronger at Mercury than at earth. Magnetopause reconnection could still impose a large electric potential, consistent with the energies of the observed accelerated particles, across Mercury's magnetosphere despite its small size. On the other hand, because the ion Larmor radius in Mercury's magnetosheath is a larger fraction of its magnetospheric scale size than at earth, turbulent hydromagnetic viscosity could be more important at Mercury. Because of Mercury's large size relative to its magnetosphere, absorption by the planet eliminates a trapped radiation zone and probably strongly affects the hydromagnetic flow within the magnetosphere. The absence of a significant ionosphere of atmosphere at Mercury may mean that the electric fields generated by the hydromagnetic flow might couple directly to the resistive surface of the planet, making the flow fundamentally different from those at earth or Jupiter. Mercury has the only known planetary magnetosphere without an atmosphere-ionosphere coupling.

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

THE MAGNETOSPHERES OF SATURN, URANUS, AND NEPTUNE

Both Saturn and Uranus are scheduled for a first flyby reconnaissance in the 1980's. Saturn almost certainly has and Uranus probably has a substantial magnetosphere. Low-frequency radio bursts–similar to Jovian decametric radio bursts–have been detected from Saturn. Empirical scaling arguments suggest that Saturn, Uranus, and Neptune have surface magnetic field strengths the order of 1 G, implying that each planet has a large magnetosphere with a magnetopause radius exceeding ten times the planetary radius. Because Saturn, Uranus, and Neptune all rotate rapidly, their outer magnetospheres may resemble Jupiter's more than earth's. Saturn's satellite, Titan, has a massive atmosphere that could be an important source of magnetospheric ions, just as Io's atmosphere is at Jupiter. While Io is in the relatively quiet inner region of the Jovian magnetosphere, Titan may be in a region corresponding to the outer time-variable zone of Jupiter's magnetosphere. Following the Galileo mission to Jupiter, an exploration by orbiter of Saturn's magnetosphere will be the next logical step in the comparative study of the magnetospheres of the outer planets.

The rotation axis of Uranus, which, unlike those of all other planets, lies nearly in the ecliptic plane, will be directed along the sun–Uranus line in 1988. If Uranus has a dipolar magnetic field like those of other planets, its dipole axis will be aligned more or less along its rotation axis. Uranus probably provides the opportunity to explore the only "pole-on" magnetosphere in the solar system.

The solar wind is far more time variable in the outer solar system than it is near earth. The interaction and steepening of fast streams lead to regions of strong solar-wind compressions and rarefaction. Therefore, the magnetospheres of Saturn and Uranus may be at least as, and possibly more, time variable as that of Jupiter.

The effects of ionization of interstellar neutrals in the vicinity of Uranus and Neptune may be important. Interstellar neutrals might compete with the solar wind in determining their magnetospheric properties even at the present epoch, which is characterized by anomalously low interstellar densities in the solar neighborhood. At other epochs, the interstellar source might possibly dominate, especially when the heliosphere is immersed in a high-density interstellar cloud and when even earth's magnetosphere might be affected.

THE INTERACTION OF THE SOLAR WIND WITH VENUS, MARS, AND COMETS

A body with an intrinsic magnetic field too weak to deflect the solar wind does not have a classical magnetosphere. Since Venus has very little shielding because of an intrinsic magnetic field, its dense atmosphere interacts directly with the solar wind. Recent Pioneer/Venus results indicate that the solar wind affects the mass, species, and energy balance of the upper atmosphere of Venus. Venus also has a magnetic tail due to induction, whereby the solar-wind electric field drives currents in the Venusian ionosphere that then create a magnetic field.

Unlike Venus, Mars appears to have a magnetic field sufficiently strong to stand off the solar wind most of the time; its extrapolated magnetopause is usually well above the ionosphere. However, there is also evidence that the solar wind may interact directly with the ionosphere of Mars, perhaps intermittently.

One problem critical to an understanding of the hydromagnetic envelopes of both Venus and Mars is to resolve the relative importance of intrinsic and induced magnetic fields. Knowledge of their intrinsic dipole moments is important to planetary dynamo theory. Recent Pioneer/Venus results suggest that the magnetic field of Venus is largely induced. The dipole moment and orientation of the intrinsic field of Mars are in doubt. To separate intrinsic from induced fields, it is necessary to monitor continuously the magnitudes and delay times of their ionospheric responses to solar-wind variations. How the solar wind affects the mass and energy balance of the upper atmospheres of both Mars and Venus is an equally critical problem, to both magnetospheric and atmospheric physics.

The theoretical and experimental program for Venus and Mars are at an early exploratory phase. The Pioneer/Venus mission is providing the United States with a large variety of highly resolved measurements close to Venus. Mars deserves similar treatment. *Although the United States has orbited many spacecraft about Mars, only the Mariner 4 flyby included instrumentation to study the interaction of Mars with the solar wind. Inclusion of solar-wind interaction studies on a future Mars mission is needed to fill an important hole in comparative magnetospheric studies.*

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

Despite the many unanswered questions, our ignorance of the interaction of Mars and Venus with the solar wind pales in comparison with our ignorance of comets. *In situ measurements are needed to define the basic properties of the interaction of the solar wind with a comet.*

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

COMPARATIVE PLANETARY ATMOSPHERES

The comparative study of planetary atmospheres can help us to gain a better fundamental understanding of atmospheric processes in general and possibly to identify terrestrial processes that would otherwise be missed. Since the planets have widely differing masses, rotation periods, surface characteristics, atmospheric constituents, atmospheric time constants, and solar insolations, specific atmospheric processes can be isolated and compared with similar processes occurring in the earth's atmosphere. Public interest in the earth's climate has grown considerably in the past decade, centering on how the climate might change in response to possible changes in solar flux, volcanic activity, and increases in the CO_2 content resulting from the burning of fuels. Although it is not absolutely necessary to study other planets to understand the process influencing terrestrial weather and climate, valuable insights can be gained by studying these processes in different forms in the atmospheres of the planets.

The atmosphere of Mars has been more extensively studied by spacecraft than that of any other planet except earth. Earth and Mars are similar in size, temperature regimes, and rotation rate. On the other hand, the Martian atmosphere is made up of about 95 percent CO_2 and has a surface pressure less than 1 percent that on earth. Measurements made from orbiting spacecraft have revealed large latitudinal and seasonal temperature variations and strong stability with respect to vertical motion. Atmospheric tides and gravity waves are prominent dynamical processes in the Martian atmosphere. Substantial wind velocities, up to 60 $msec^{-1}$, have been inferred from motions of discrete clouds measured from Viking. Global dust storms and meridional flows toward or away from the polar caps are unique features of the Martian circulation.

The atmospheric energy cycle and dynamics of Mars are dependent on condensate clouds, suspended dust particles, and radiatively active CO_2. Radiation exchange over the winter pole is affected by thick condensate clouds, while, in the nonpolar regions, the radiation exchange is primarily determined by the radiative properties of CO_2 and suspended dust. The processes controlling the exchange of CO_2 and water vapor with the surface and polar caps, their transport in the atmosphere, and their formation into clouds needs to be delineated.

The sensitivity of the thin atmosphere to dust loading is particularly significant. Viking observations have shown that dust opacity is substantial most of the time. Dust heating of the atmosphere can be so intense that global dust storms so produced significantly change the atmospheric temperature distribution. To understand these global storms, observations of their origin, growth, and decay, as well as the properties of the dust itself, are required.

The topographical scales on Mars are of the same order as its atmospheric scale heights. Thus, atmospheric circulation is strongly influenced by the exaggerated topography of Mars. For example, banded cloud structures may be signatures of topographically forced gravity waves. In the summer hemisphere, surface relief is imprinted in the temperature structure to great heights, while, in the winter hemisphere, the topography primarily deflects winds. Since the atmospheric system of Mars is simpler than that of earth, Mars is an excellent laboratory for testing theories of topographic forcing and the propagation of forced waves. Atmospheric observations are required on spatial scales small enough to resolve the topographic structure and on time scales small enough to resolve diurnal variability.

Our knowledge of the dynamics of the Martian atmosphere remains incomplete. Proper global coverage of the atmosphere through *in situ* and remote-sensing measurements is necessary to sort out the influence of latitude, longitude, diurnal, seasonal, and dust-related variations. Although the broad form of the general circulation on Mars is known, more information is needed on the spatial distribution and temporal variability of surface winds and pressures. Observations of the temperature structure with adequate vertical and horizontal resolution are needed to determine the structure of planetary-scale Rossby waves and to determine the height at which vertically propagating waves degenerate into turbulence. Fine-scale measurements of winds, pressures, and temperatures are also needed to test the scaling of terrestrial boundary-layer theory on Mars.

ATMOSPHERE OF VENUS

Venus has a radius, mass, density, and distance from the sun similar to earth's. On the other hand, Venus is blanketed with a hot, dry atmosphere, whose surface temperature is 700 K and whose surface pressure is 100 times as great as that on earth. This massive atmosphere is more than 90 percent CO_2, which corresponds to all the CO_2 in the earth's oceans and carbonate rocks. The mass of water in the atmosphere of Venus is 10^{-3} of that of earth. The remarkable dynamic state of the atmosphere of Venus is illustrated by comparing its rapid retrograde rotation period of about 4 days at cloud-top levels with its slow retrograde rotation period of 243 days at the surface.

The thick clouds enshrouding Venus are believed to be droplets of a solution of sulfuric acid in water. The clouds play a major role in the overall energy budget; three quarters of the sunlight absorbed by Venus may be deposited in the clouds. Thus, the thermal structure and the circulation of the atmosphere depend strongly on processes in the clouds. Although some information will be gained on cloud composition by Pioneer/Venus, few direct determinations of cloud particle composition, size and number density, optical and thermal properties, and condensation and precipitation cycles will be made.

The surprisingly strong superrotation of the atmosphere at cloud-top levels has stimulated a number of interpretations. The present data suggest that interactions between waves and mean flow play an important role. However, none of the present interpretations can be firmly established until more definitive measurements of the global circulation and temperature field are made. The measurements made by Pioneer/Venus will add considerably to our knowledge, but measurements with improved global coverage and resolution of the circulation pattern and temperature field will be required thereafter.

The photochemically active region of the atmosphere between 65 and 135 km will receive little attention during the Pioneer/Venus mission. Until we fully understand this region, basic questions concerning atmospheric composition, vertical mixing rates, stability, and evolution cannot be answered. Further information will also be required on atmospheric dynamics, including definition of global wind patterns, driving mechanisms, momentum and energy transport processes, characterization and identification of planetary waves, and intensity and distribution of turbulence.

A greenhouse mechanism is believed responsible for maintaining the high surface temperature of Venus. That is, the solar radiation that is absorbed in the atmosphere and on the surface and then re-emitted in the infrared is kept from escaping by the dense CO_2 atmosphere and the deep, planetwide cloud deck. There is some evidence that the atmosphere of Venus was not so dense and hot in its early history but was produced over a long period of time by a runaway greenhouse mechanism that eventually drove off most of the CO_2 from the surface. One important question is whether the earth's atmosphere will evolve in a manner similar to that of Venus, especially since man is rapidly increasing the CO_2 content of the atmosphere.

JUPITER'S ATMOSPHERE

Jupiter's large size and mass, rapid rotation rate, composition and unique circulation patterns, and cloud decks put a severe test on atmospheric models. The atmosphere of Jupiter has been studied for centuries by telescope. More recently, Pioneer and Voyager spacecraft have provided a wealth of information not obtainable from earth-based observatories. The visual appearance of Jupiter is dominated by clouds; most prominent are the Great Red Spot and banded features organized on lines of constant latitude. A number of cloud features last from decades to centuries. Such persistence may be due to the long radiation time constant of the atmosphere. Jupiter's atmosphere contains several cloud layers, where the visible upper layer is composed of ammonia ice. Little is known about vertical cloud structure and cloud-forming gaseous constituents below the cloud tops. Observations of water in cloud-free areas indicate an abundance about an order of magnitude less than a solar composition mixture. Thus, it is important to know if massive water clouds are present below the visible ammonia ice clouds. Some theories of large-scale circulation suggest that latent heat release plays an important role in the dynamics. If this is the case, an understanding of Jovian cloud dynamics may provide clues to terrestrial cloud dynamics problems.

15 Levels of Investigation

In *Report on Space Science 1975*, the Committee on Planetary and Lunar Exploration (COMPLEX) identified three stages of space investigations. *Reconnaissance*—the first penetration of a region of space by an instrumented spacecraft—has discovery as its objective. Reconnaissance is followed by *exploration*, whose aim is phenomenological identification of important processes. With phenomenology clear and physical processes identified, *intensive study* begins. Here, research focuses on quantitative evaluation of physical mechanisms and their linkage one to another in comprehensive models.

The COMPLEX categorizations apply equally well to *in situ* spacecraft investigations in solar-system space physics. Slightly different ones apply to remote-sensing studies. Detection and first preliminary surveys are followed by global surveys with sufficient coverage and resolution to identify basic physical mechanisms. These are again followed by intensive studies, usually requiring high space and time resolution, whose aim is quantitative understanding of specific processes. In addition, most of our major subdisciplines can use or have made use of active experiments. Because of their diversity it is difficult to identify all but two extreme levels of investigation. The first exploratory uses of a given technique determine its feasibility and identify research objectives. At the opposite extreme is its systematic use to produce basic physical information. In Table 15.1, we estimate the present status of *in situ* spacecraft investigations and their future status assuming completion of NASA's currently approved program, and, in Tables 15.2 and 15.3, of remote-sensing investigations and selected active experiments.

When research approaches its intensive study phase, one can judge its progress by the quantitative understanding it has achieved. One way to do so is to

TABLE 15.1 Levels of *in situ* Spacecraft Investigation

Disicipline	Subject Area	Awaiting Reconnaissance	Reconnaissance	Exploration	Intensive Study
Solar physics	Sun and solar corona	X			
Heliospheric physics	Generation region of solar wind	X			
	High-latitude solar wind		SPM		
	In-ecliptic solar wind beyond Saturn				
	In-ecliptic solar wind between Mercury and Jupiter				
	Heliopause and interstellar medium	X			
Terrestrial, magnetospheric physics	Magnetosphere within 60 R_e				
	Earth magnetic tail and wake		X		

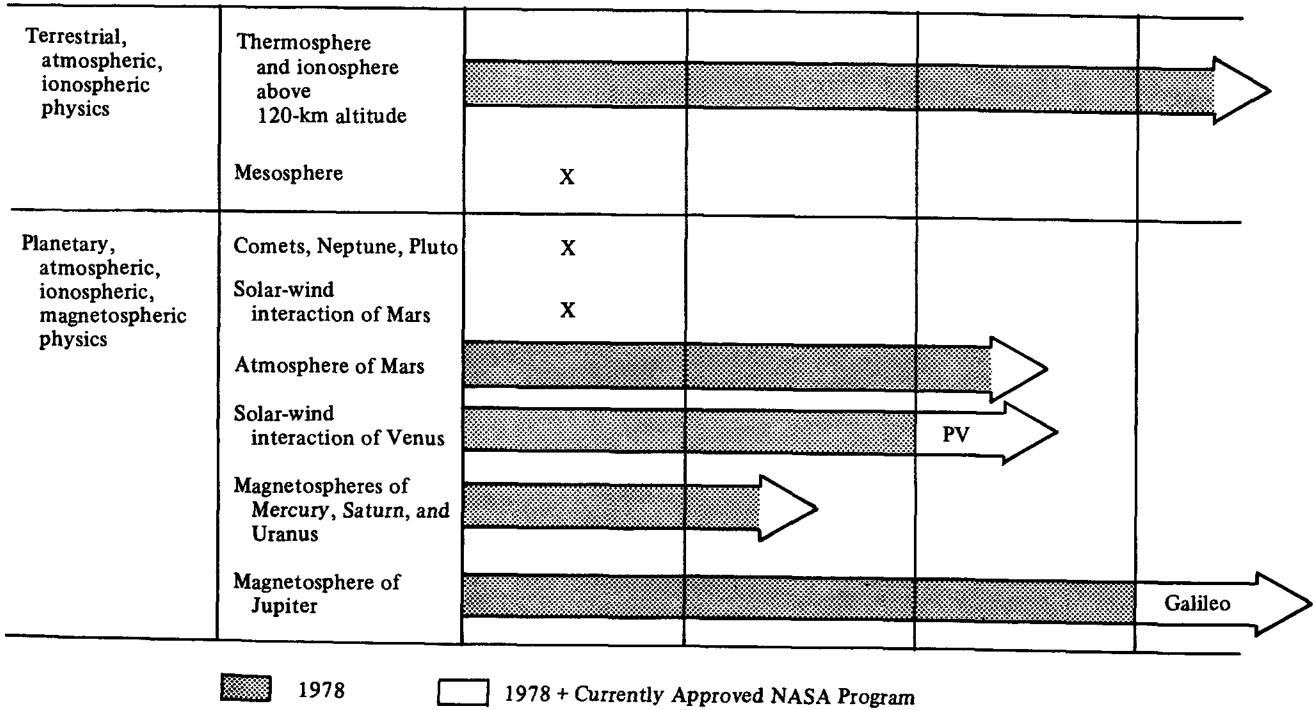

Terrestrial, atmospheric, ionospheric physics
Thermosphere and ionosphere above 120-km altitude
Mesosphere
X
Planetary, atmospheric, ionospheric, magnetospheric physics
Comets, Neptune, Pluto
X
Solar-wind interaction of Mars
X
Atmosphere of Mars
Solar-wind interaction of Venus
PV
Magnetospheres of Mercury, Saturn, and Uranus
Magnetosphere of Jupiter
Galileo
1978
1978 + Currently Approved NASA Program

TABLE 15.2 Levels of Remote-Sensing Investigations

Discipline	Subject Area	Awaiting Preliminary Survey	Preliminary Survey	Global Survey	Intensive Study
Solar physics	Solar coronal holes, large-scale magnetic fields				
	Solar radio bursts				
	Solar global oscillations				
	Solar flares			SMM	
Heliospheric physics	Interstellar neutrals				
Terrestrial, magnetospheric physics	Global auroral morphology			DE	
	Remote sensing of magnetospheric structure	X			
Terrestrial, atmospheric, ionospheric physics	Mesosphere			SME	

▒ 1978 □ 1978 + Currently Approved NASA Program evaluate comprehensive models that link together several interacting processes. Here we have defined four evolutionary phases. The first is phenomenological *identification* of pertinent physical processes and their interactions. This done, it becomes feasible to construct *preliminary quantitative models*. Whether they are correct or not, their existence signifies that moderate quantitative understanding has been achieved. They motivate further observations and theory leading to *accurate* quantitative models, suitable for systematic comparison with experiment. These then evolve into predictive models, at which point the threshold of practical utility has been reached. Table 15.4 contains our perception of the 1979 status of models of several problems in solar-system space physics, selected for their illustrative value. Those problems underlined in the table have significant plasma components. The recent SSB report *Space Plasma Physics: The Study of Solar-System Plasmas* (National Academy of Sciences, Washington, D.C., 1978) has argued that progress on such problems is limited by our weak understanding of certain basic plasma processes, such as magnetic field reconnection. Table 15.4 appears to communicate the same message.

Uneven levels of investigation impede intensive studies in each area. For example, lack of *in situ* measurements near the sun limits interpretations of our intensive remote-sensing studies; lack of *in situ* high heliographic latitude measurements limits understanding of many investigations of the solar wind in the ecliptic plane; lack of measurements in the deep geomagnetic tail prevents full understanding of the magnetosphere's response to the changing solar wind despite 20 years of intensive study within 60 R_e; poor knowledge of the mesosphere limits our understanding of how the upper atmosphere, ionosphere, and magnetosphere couple to the lower atmosphere; and, finally, our understanding of the interaction of Mars with the solar wind is much poorer than our understanding of that of Mercury, Venus, earth, and Jupiter.

TABLE 15.3 Levels of Investigation of Selected Active Experimental Techniques

Technique	Subject Area	Not Yet Used	Preliminary Use	Systematic Use
Radar	Ionospheric, atmospheric, and solar physics			
Energetic particle injections	From rockets in earth's ionosphere and magnetosphere			
	From spacecraft in earth's ionosphere and magnetosphere	SPACELAB I		

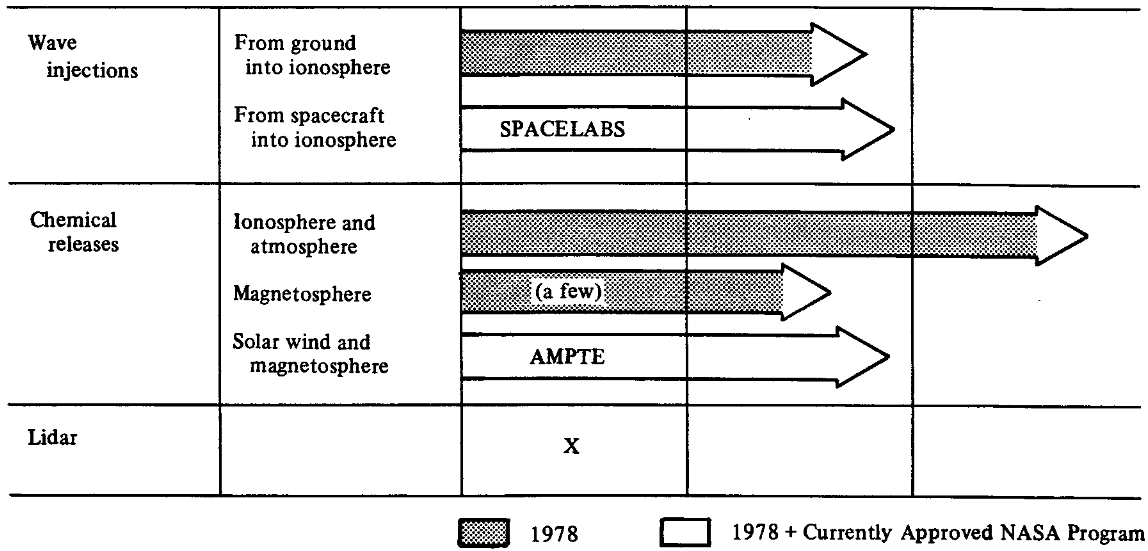
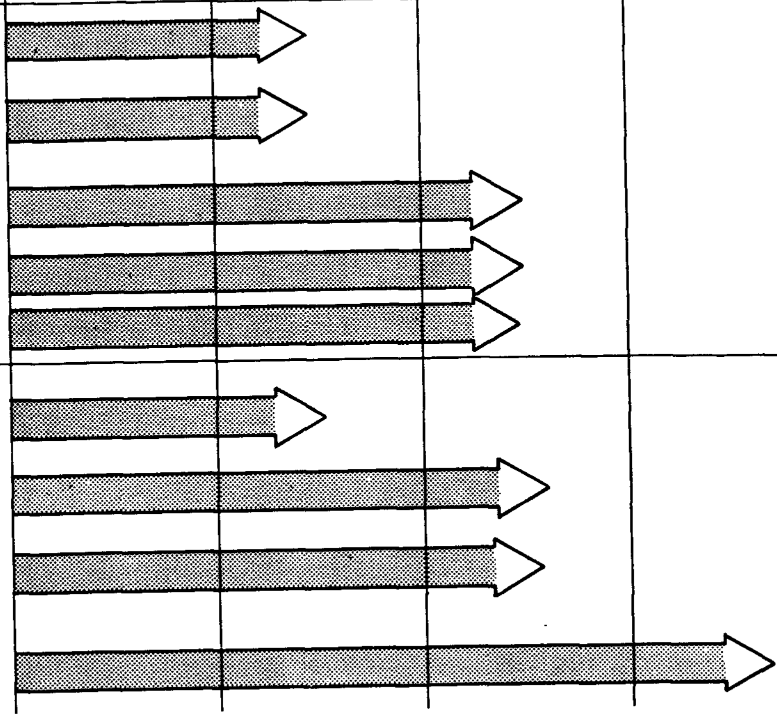

Wave injections
From ground into ionosphere
From spacecraft into ionosphere
SPACELABS
Chemical releases
Ionosphere and atmosphere
Magnetosphere
(a few)
Solar wind and magnetosphere
AMPTE
Lidar
X
1978
1978 + Currently Approved NASA Program

TABLE 15.4 1978 Status of Physical Models

Discipline	Problem	Rudimentary Understanding	Some Phenomenological Understanding	First Quantitative Models	Accurate Quantitative Models	Predictive Models
Solar physics	Basic flare mechanism					
	Large-scale weak magnetic field					
	Nonradiative heating of atmosphere					
	Global oscillations					
	Thermal flare plasma					
Heliospheric physics	Interplanetary acceleration of energetic particles					
	Coronal expansion					
	Interplanetary modulation of galactic cosmic rays					
	Evolution of solar-wind structures					



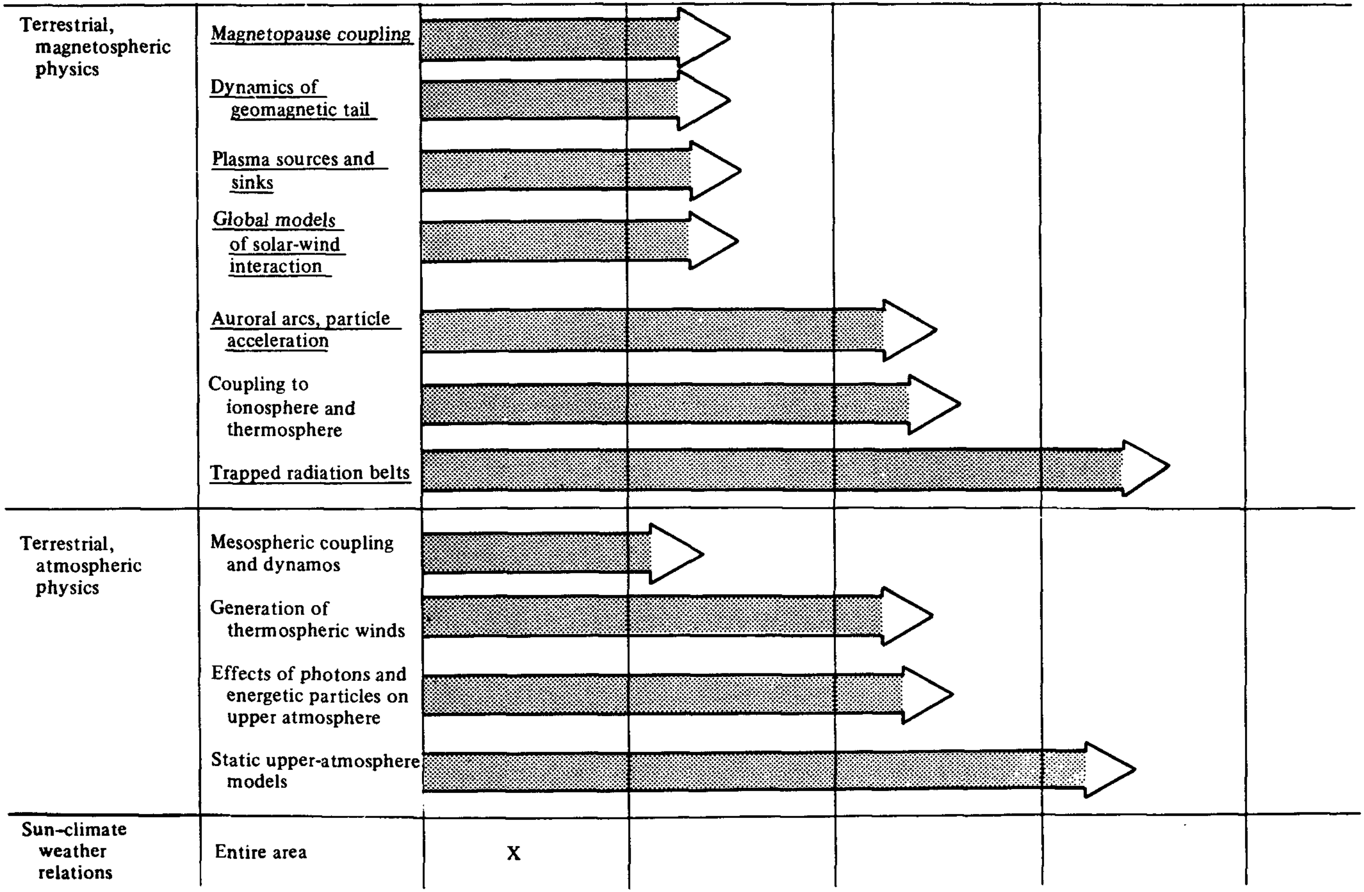

Terrestrial, magnetospheric physics
Magnetopause coupling
Dynamics of geomagnetic tail
Plasma sources and sinks
Global models of solar-wind interaction
Auroral arcs, particle acceleration
Coupling to ionosphere and thermosphere
Trapped radiation belts
Terrestrial, atmospheric physics
Mesospheric coupling and dynamos
Generation of thermospheric winds
Effects of photons and energetic particles on upper atmosphere
Static upper-atmosphere models
Sun–climate weather relations
Entire area
X

TABLE 15.4 (Continued)

Planetary magnetospheres, ionospheres, and atmospheres	Magnetospheres of Mars, Saturn, Uranus, Neptune, Pluto, and comets	X				
	Magnetospheres of Mercury, Venus, and Jupiter					
	Static models of planetary atmospheres					