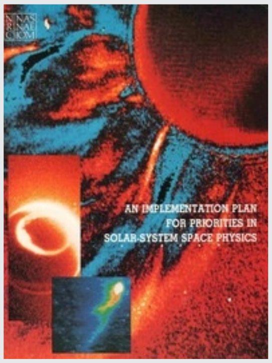

An Implementation Plan for Priorities in Solar-System Space Physics

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AN IMPLEMENTATION PLAN FOR PRIORITIES IN SOLAR-SYSTEM SPACE PHYSICS

Committee on Solar and Space Physics
Space Science Board
Commission on Physical Sciences, Mathematics, and Resources

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SPACE SCIENCE BOARD

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

FOREWORD

For the last several years the Space Science Board has been developing strategies for guiding future research programs in the various scientific disciplines involved in space research. This report, however, has a somewhat different character. While it does specify the scientific objectives of the field (thereby updating the previous report, *Solar-System Space Physics in the 1980's: A Research Strategy*, NAS, 1980), it goes further and describes the plan for implementing the objectives. In this sense, the report more closely follows the methodology of two recent reports that have received wide acclaim for establishing priorities in related fields of research, *Astronomy and Astrophysics for the 1980's* (NAS, 1982) and *Planetary Exploration Through Year 2000* (NASA, 1983).

The Space Science Board (SSB) adopted this different approach for this report for two reasons. First, with the appearance of the astronomy and planetary priorities reports, a need was established to do something similar in solar and space physics. Secondly, with NASA currently involved in preparing a priorities report for the Earth Sciences, it was decided that the SSB could provide a valuable service for this broad-based effort by undertaking a part of the subject matter for which the Board was admirably suited through the Committee on Solar and Space Physics (CSSP). NASA concurred in this decision.

Thus, in November 1983, the Board directed the CSSP to develop a priorities-based study of solar and space physics, using the 1980 Research Strategy as a basis. The Committee produced the following report, which was reviewed and approved by the Board in November 1984.

Thomas M. Donahue
Chairman, Space Science Board

PREFACE

In carrying out the charge of the Space Science Board, stated above, the Committee on Solar and Space Physics (CSSP) proceeded by organizing three separate panels as follows: solar and heliospheric physics under George L. Withbroe; magnetospheric plasma physics under Robert W. Fredericks; and upper atmosphere physics under Darrell F. Strobel. Each panel was asked to solicit inputs from the scientific community in each discipline area on what constitutes the highest priority science and the optimum means for carrying it out.

The resulting sets of science objectives and programmatic priorities, along with estimated costs, were organized on a timeline from FY 86 through the year 2000 by each panel. The full committee examined critically the work of the panels and, after several iterations, a composite Implementation Plan was agreed upon. This preliminary plan was presented by committee members to several scientific groups beginning in the spring of 1984; during these sessions comments and suggestions were solicited. The inputs thus received were considered by the committee, and a draft version of the report was circulated to over 70 colleagues representing most institutions active in the field of solar and space physics. Comments and suggestions were received from about half, and the committee redrafted the document in October 1984 for presentation to the SSB's November meeting for approval. This extensive interaction with the community has produced a prioritized Implementation Plan that is supported by most members of the scientific disciplines involved.

Our report is published in two parts, the Executive Summary and the main body. The Executive Summary presents the prioritized program, summaries of the scientific objectives and recommended missions, near-term budget decisions, and connections to basic physics, astrophysics, and earth system studies. This part is intended to quickly familiarize the reader with the substance of the science being addressed and the essential conclusions and recommendations of this study. Although it can stand alone, it should be read in conjunction with the main body.

The main body of the report describes the detailed science objectives for future research, the most significant accomplishments of the past research, the way in which the Implementation Plan was constructed, the detailed mission plans of each of the major sub-disciplines of solar and space physics research, and some additional thoughts on the general health and conduct of our science.

An undertaking of this magnitude required the assistance of many individuals and institutions, too numerous to mention. We owe special thanks to Marshall Space Flight Center for hosting one of our meetings, to Goddard Space Flight Center and the Jet Propulsion Laboratory for assistance on cost estimates for some projects, and, most importantly, NASA Headquarters for providing the background information necessary for putting together the Implementation Plan. We are grateful to Drs. J.D. Bohlin and S.D. Shawhan of NASA who participated in some of our meetings and provided important information whenever needed. Dr. T.M. Donahue, Chairman of the SSB, gave us important guidance in the formulation of this plan. Many of our colleagues commented on several drafts of this document. We are especially grateful to Dr. D.J. Williams for assistance in the selection and placing of figures included in this report. The work of Mrs. Carmela Chamberlain and Mrs. Pat Johnson in typing the innumerable drafts of this report is most appreciated, as is the work of Mrs. Angelika Peck, who did the design and layout for the Executive Summary. Finally, we are grateful to our Executive Secretary, Dr. Richard C. Hart, whose untiring efforts and advice were invaluable to the completion of this report.

S.M. Krimigis, Chairman
Committee on Solar and Space Physics

1 INTRODUCTION

Man's wonder at the manifold phenomena in the environment and the drive to understand and use them have led to modern science. To understand the relationship between natural events on the Earth and changes in the Sun has been one of man's lasting intellectual quests. The scientific discipline we now know as solar system space physics is the modern culmination of efforts to comprehend the relationships among a broad range of naturally-occurring physical effects including solar phenomena, terrestrial magnetism, and the aurora. Understanding the solutions to these basic physics problems requires the study of ionized gases (plasmas), magnetohydrodynamics, and particle physics.

Space physics as an identifiable discipline began with the launch of the first Earth satellites in the late 1950s and the discovery in 1958 of the Van Allen radiation belts. The phenomena associated with this field of study are among the earliest recorded observations in many parts of the world The ancient Greeks were puzzled by "fire" in the upper atmosphere that we now call the aurora; there are several possible references to the aurora in ancient Chinese writings before 2000 B.C.; there are also passages in the first chapter of Ezekiel with vivid descriptions of what we now recognize as auroral formations.

The observation of sunspots by Galileo in 1610 led to the eighteenth century discovery of the 11-year solar sunspot cycle and the recognition that there was a connection between sunspot variability and auroral activity. The large reduction of sunspots during the second half of the seventeenth century during a period of unusually cool weather in Europe suggests a tantalizing connection between some aspects of solar activity and climate.

This possible link between solar activity and terrestrial phenomena could not be studied in detail until this century. We now know that, in addition to the atmosphere that surrounds us, there exists a region, at higher altitudes, consisting of an electrically conducting plasma permeated by the Earth's magnetic field. It is called the "magnetosphere" because its structure and many of its processes are controlled by the magnetic field. Since the early years of the space program, we have learned that the Sun has its own magnetosphere consisting of a hot (million-degree Kelvin) magnetized plasma wind (the solar wind) that extends beyond the orbits of the planets and fills interplanetary space, forming a distinct cavity in the nearby interstellar medium—the "heliosphere."

Using knowledge gained over the past 25 years, we can now begin to identify some of the physical mechanisms linking the Sun to our near-Earth environment. For example, motions in the convective layers of the Sun are believed to generate the solar magnetic field and solar wind variations; these in turn affect the Earth's magnetosphere and regulate the amount of plasma energy incident on the Earth's polar caps. Associated magnetospheric activity drives strong winds in the upper atmosphere and may influence the dynamical and chemical composition of the mesosphere and stratosphere as well. The upper atmosphere, in turn, is the major source of heavy ions in the magnetosphere. Further, current research suggests that small percentage changes (about 0.5 percent) in the total energy output of the Sun (the solar "constant") may influence short-term terrestrial climate. These and other speculative suggestions should be addressed as part of a comprehensive research program in solar-terrestrial physics because of their potential importance for the Earth. Indeed, the Earth and its space environment contain coupled phenomena and need to be studied as a system—from the Sun and its plasma environment to the Earth's magnetosphere, atmosphere, oceans, and biota.

Discoveries in solar and space physics over the past 25 years have inspired a number of developments in theoretical plasma physics. Concepts in charged particle transport theory, developed to describe the behavior of energetic particles in the solar wind and magnetosphere, are routinely used in studying extragalactic radio sources and laboratory plasmas. Magnetic field reconnection (involving the explosive conversion of electromagnetic energy into particle energy), collisionless shock waves, electrostatic shocks, and hydromagnetic turbulence are also among the fundamental plasma phenomena first studied and elucidated in analysis of solar and space plasmas.

Subsequently, these and other concepts have found application to related branches of plasma physics, such as nuclear fusion. The development of space plasma physics since the 1960s has influenced nuclear fusion research. Pitch-angle scattering and magnetic reconnection are now tools of laboratory plasma theory, while ideas developed in fusion work have influenced space plasma science in important ways. Thus, the language of plasma physics links two very important scientific endeavors: the search for a limitless supply of clean energy through thermonuclear fusion and the exploration and understanding of our solar system environment, most of which is in the plasma state.

New concepts developed in studies of solar and space plasmas find important applications to astrophysical problems as well as to laboratory plasmas. For example, the structure of collisionless shock waves can be resolved only by spacecraft instruments. Such shocks are invoked in some current models of star formation. Furthermore, the study of propagating interplanetary shocks has contributed to understanding and modeling of acceleration of cosmic rays by shocks. Particle acceleration via direct electric fields, observed in the Earth's magnetosphere, has been invoked in acceleration models of pulsar magnetospheres. The subject of cosmic-ray transport owes much to detailed in situ studies of the solar wind. Some stellar winds are thought to be associated with stars that, like the Sun, have convective outer layers, while winds of more massive stars are driven by radiation pressure. Explanations of physical phenomena in astrophysical objects that will remain forever inaccessible to direct observation rest heavily on insights obtained through studies of solar system plasmas accessible to in situ observations.

Even though space plasma physics is a mature subject, new observations continue to reveal facets of the physics not recognized previously. For example, observations of "spokes" in Saturn's rings seemed to highlight the importance of electromagnetic forces on charged dust particles. Similarly, the interaction of dust and plasma in comets is thought to be a central element in understanding the formation of comet ion tails. Such observations have given rise to the study of "gravito-electrodynamics" in dusty plasmas, which in turn has important applications to the understanding of the formation and evolution of the solar system, as pointed out by Alfven some years ago.

The understanding of the near-Earth space environment is not only a basic research enterprise; it also has extremely important practical aspects. Space is being used increasingly for many different scientific, commercial, and national security purposes. Well-known examples include communications and surveillance satellites and such scientific platforms as the Space Telescope and the Space Station. These space vehicles must function continuously in the near-Earth environment, subject to the dynamic variations of the heliosphere, the magnetosphere, and the upper atmosphere. It is well-established that many spacecraft systems and subsystems exhibit anomalies, or even failures, under the influence of magnetospheric substorms, geomagnetic storms, and solar flares. Processes such as spacecraft charging and "single-event upsets" (owing to highly ionizing energetic particles) in processor memories make the day-to-day operation of space systems difficult. Finally, these aspects of the near-Earth environment become particularly important in view of the planned long-term presence of man in space. The complement of programs outlined in this report will allow us to model the global geospace environment and will thus allow us to develop a global predictive capability. This, in turn, should permit substantial improvements in our abilities to operate all space-based systems in the near-Earth region.

We have advanced well beyond the exploratory stages in solar and space physics, with some notable exceptions—the solar interior, the environment near the Sun where the solar wind is accelerated, the atmospheres of some of the planets, and the boundary of the heliosphere. The phenomenological approach appropriate to a young science still in its discovery phase has progressed to a more mature approach where focussed and quantitative investigations are made, where interactive regimes are studied, and where theory and modeling play a central role in advancing understanding.

The future solar and space physics program will require tools and techniques substantially different from those of the past. Continued progress will require development of complex, multifaceted, experimental and observational projects that will be technologically challenging. We believe that the anticipated scientific contributions fully justify the proposed undertakings.

The purpose of this report is to develop an overall program of space research that will address the most significant scientific problems, that will clearly define the priority of investigations, and that will be affordable by NASA.

Several other reports that are related to this document have appeared in recent years. The Colgate report (*Space Plasma Physics: The Study of Solar-System Plasmas*, NAS, 1978) reviewed the status of the field and concluded that "space plasma physics is intrinsically an important branch of science." The Kennel report (*Solar-System Space Physics in the 1980's: A Research Strategy*, NAS, 1980) laid out the scientific goals and objectives for the field. Other reports (*Solar-Terrestrial Research in the 1980's*, NAS, 1981; *National Solar-Terrestrial Research Program*, NAP, 1984) integrated the ground-based segment of the field and stated priorities for its implementation. *The Physics of the Sun* (NAP, 1985) reviewed the scientific content of solar physics and described future research directions. *A Strategy for the Explorer Program for Solar and Space Physics* (NAP, 1984) emphasized the need for a revitalized Explorer program for solar and space physics and outlined several specific examples of scientific investigations.

In addition, two other recent reports have developed prioritized programs in related sciences: astronomy, *Astronomy and Astrophysics for the 1980's* (NAP, 1982); and planetary science, *Planetary Exploration Through Year 2000* (NASA, 1983). Our report is similar to these in that it is intended to develop the implementation plan for NASA's solar and space physics program that will accomplish the aims of our scientific strategy.

2 GUIDING PRINCIPLES

The scientific goals established by the Kennel report remain the guiding force of this science. The two principles that served as the foundation for the design of the strategy remain extant:

- "The objectives of solar-system space research are to understand the physics of the Sun, the heliosphere, and the magnetospheres, ionospheres, and upper atmospheres of the Earth, other planets, and comets.
- Studies of the interactive processes that generate solar radiation and link it to the Earth should be emphasized, because they reveal basic physical mechanisms and have useful applications . . . ."

3 SCIENCE STATUS AND OBJECTIVES

The following summary of the status of the subject and the scientific objectives are adapted from the Kennel report (*Solar-System Space Physics in the 1980's: A Research Strategy*, NAS, 1980) with appropriate changes and updates.

Solar Physics

Major advances in our understanding of the Sun were made in the 1970s and the early 1980s (see Figure 1). Most, if not all, of the magnetic flux that emerges from the convective zone is subsequently compressed into small regions of strong field (1200-2000 G), a process that is still not understood theoretically. Observations confirmed earlier predictions that the 5-minute photospheric oscillation, discovered in the early 1960s, is a global phenomenon. This discovery has made "helio-seismology" possible, by which the depth of the convective zone and the rotation below the photosphere have been inferred. 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 among the major discoveries of the 1970s. White-light, EUV, and x-ray observations suggested how coronal holes are related to the convective zone and to the solar wind. Skylab observations unambiguously identified magnetic arches as the basic structure of coronal flares. This perception altered our theoretical picture of solar flares and clarified the need for a coordinated multi-instrument attack, which was initiated with the Solar Maximum Mission (SMM).

To better understand 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, is linked to luminosity modifications, 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 solar-flare energy is released to the heliosphere; and
- the energy sources and composition of the solar atmosphere and corona and the physics of the Sun's large-scale weak magnetic field.

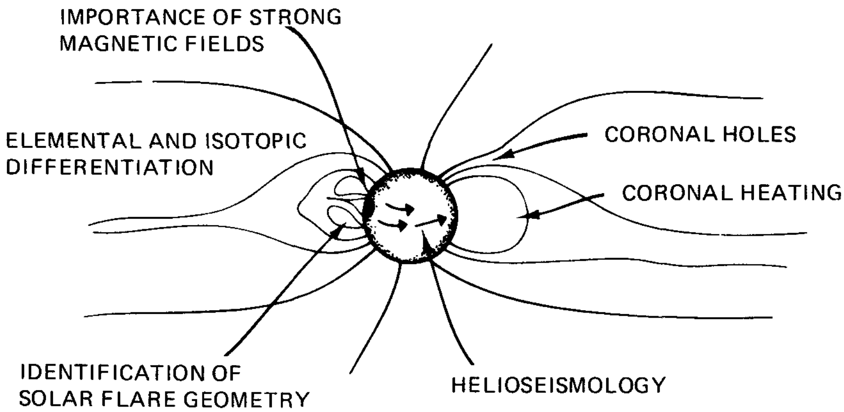
Physics of the Heliosphere

The Sun is the only stellar exosphere where complex phenomena common to all stars can be studied in situ. Observations of the Sun and the heliosphere, the plasma envelope of the Sun extending from the corona to the interstellar medium, provide the basis for interpreting a variety of phenomena ranging from x-ray and gamma-ray radiation to cyclical activity and long-term evolution. The Sun, together with the heliosphere and planetary magnetospheres and atmospheres, comprises an immense laboratory that exhibits complex magnetohydrodynamical (MHD) and plasma physical phenomena whose study enhances our understanding of basic physical laws as well as our understanding of the influences of the Sun on our terrestrial environment.

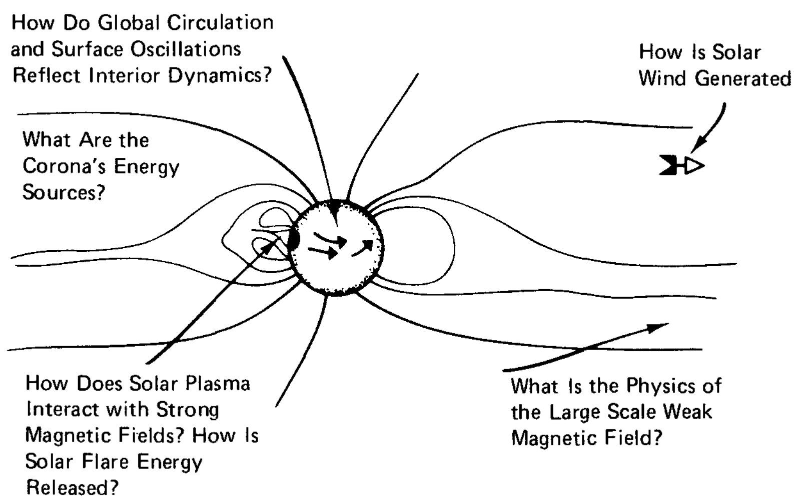
The solar wind has been studied near the Earth since 1961. At the present time, measurements of the solar wind have been extended to within Mercury's orbit (0.3 AU) and past Pluto's orbit but have been confined to near the ecliptic plane. Quantitative models of high-speed solar-wind streams and flare-produced shocks have been 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 has reoriented much solar wind research. The sector structure of the solar wind has been unambiguously 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 have been 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 en-

A SOLAR PHYSICS—RECENT ACCOMPLISHMENTS



B SOLAR PHYSICS—OBJECTIVES



C SOLAR PHYSICS—REQUIRED MEASUREMENTS

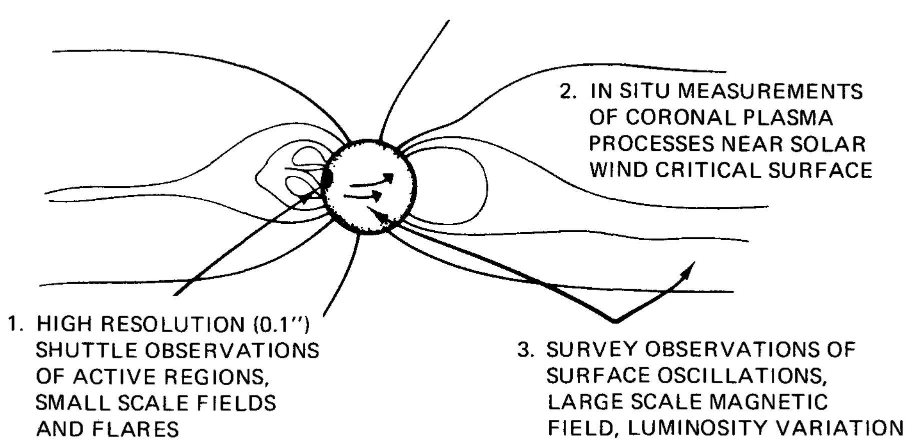


FIGURE 1 Solar physics: status, objectives, and recommendations. In this series of sketches of the Sun and its coronal magnetic field we illustrate some recent accomplishments in solar physics (A), questions that can be fruitfully attacked in the 1980s and 1990s (B), and the principal research programs 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.

ergy, momentum, energetic particles, plasma, and magnetic fields through interplanetary space, we need to study the following:

- first and foremost, the solar processes that govern the generation, structure, and variability of the solar wind;
- the three-dimensional properties of the solar wind and heliosphere; and
- the plasma processes that regulate the transport and acceleration of energetic particles throughout the heliosphere.

Magnetospheric Physics

New processes regulating Earth's magnetic interactions with the solar wind were discovered in the 1970s and early 1980s (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 reevaluation 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 concurrent state of the solar wind has not been unambiguously quantified even today.

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

- the transport of energy, momentum, plasma, and magnetic and electric fields across the magnetopause, through the magnetosphere and ionosphere and into or out of the upper atmosphere;
- the storage and release of energy in the earth's magnetic tail;
- the origin and fate of the plasma(s) within the magnetosphere; and
- 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 provide a source of nitrogen 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 (AE), 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 complete the description of the 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 fully the entire upper atmosphere and its interaction with the sun and the magnetosphere, we should study the following (see Figure 3C):

- the radiant energy balance, chemistry, and dynamics of the mesosphere and stratosphere and their interactions with atmospheric regions 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; and
- the effects of variable photon and ener-

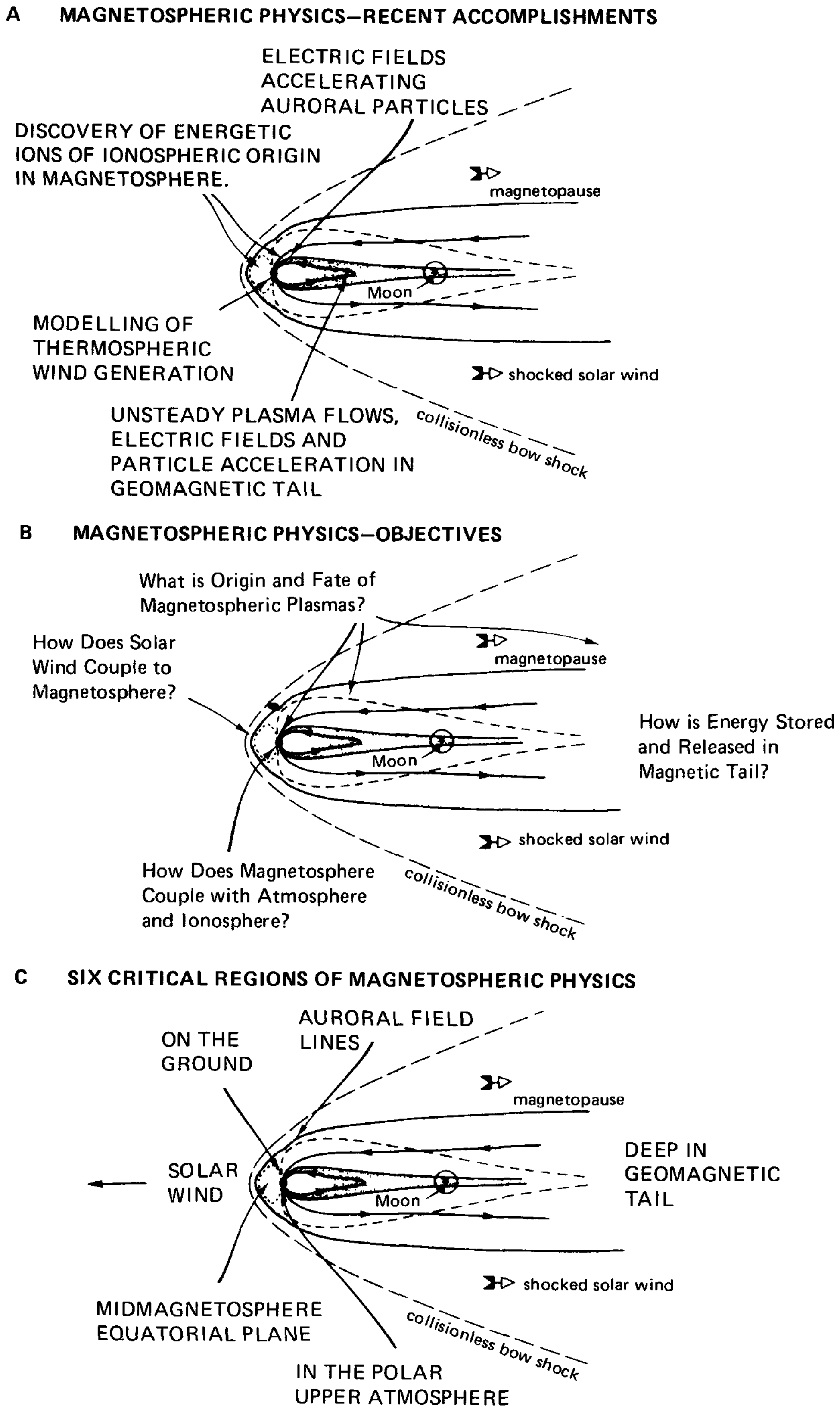


FIGURE 2 **Magnetospheric physics: status, objectives, and recommendations. Shown here is the Earth's magnetosphere—the cavity formed by the interaction of the solar wind with the Earth's magnetic field. A collisionless bow shock stands upstream of the magnetopause, the boundary separating shocked solar 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 1980s and 1990s. C illustrates the six critical regions where simultaneous studies are needed to help construct a global picture of magnetospheric dynamics.**

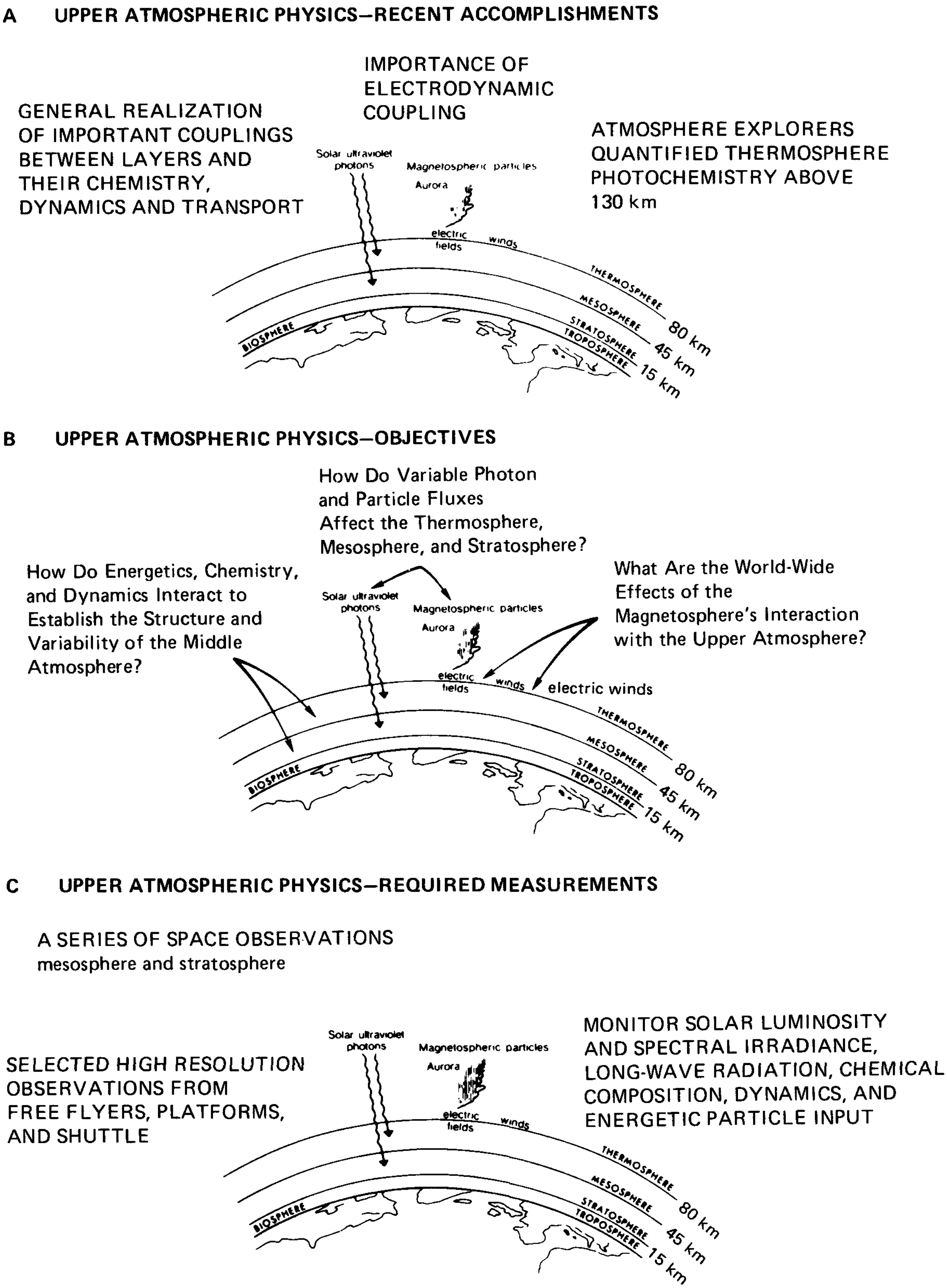


FIGURE 3 **Upper-atmospheric physics: status, objectives, and recommendations. Sketched in these figures are the layers into which the atmosphere has traditionally been divided. Our studies of these layers, and the interacting processes occurring within them, are becoming more integrated. Solar ultraviolet 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.**

getic particle fluxes on the thermosphere and on chemically active minor constituents of the mesosphere and stratosphere.

Solar-Terrestrial Coupling

Solar-terrestrial coupling is concerned with the interaction of the Sun, the solar wind, the Earth's magnetosphere, ionosphere, and atmosphere with particular emphasis on the response of the system to solar variability. For example, a solar flare produces both a strong solar-wind shock, which 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 can be 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 coupling solar perturbations to their terrestrial response; and
- 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 scientists now believe that they also reach the lower atmosphere and so affect weather and climate in ways not yet completely understood. For example, it has recently been suggested that the mean annual temperature in the north temperate zone has 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 and understand the solar physics that controls these variations; and
- ascertain whether any processes involving solar and magnetospheric variability can cause measurable changes in the Earth's lower atmosphere.

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 broader 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, magnetic fields, rotation periods, surface properties, and atmospheric chemistry, dynamics, and transport, comparative atmospheric and magnetospheric studies can help us to understand these processes in general and possibly to identify terrestrial processes that might otherwise be missed.

In the 1970s, Pioneer and Voyager spacecraft made flyby studies of Jupiter's atmosphere and magnetosphere, the largest and most energetic in the solar system. Pioneer 11 and the Voyagers encountered Saturn in 1979, 1980, and 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 its atmosphere.

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

- investigate in situ Mars' solar-wind interaction in order to fill an important gap in comparative magnetosphere and upper-atmosphere 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; and
- determine the role of atmospheres in substorms and other magnetospheric processes by orbital studies of Mercury—the only known magnetized planet without an atmosphere.

4 IMPLEMENTATION STRATEGY

Rationale

The status of solar and space physics, its science objectives, and the associated measurement objectives presented in the previous chapter have remained largely unchanged since they were first published in the Kennel report (NAS, 1980). Although significant progress has been attained in some areas [ionosphere-magnetosphere coupling following the launch of the Dynamics Explorer (DE) satellites in 1981; active experiments in the solar wind with the recent launch of the Active Magnetospheric Particle Tracer Explorer (AMPTE)], most of these objectives have remained unfulfilled.

As is evident from the preceding chapter, the scientific content of solar and space physics is broad, involving several important regions within the solar system—the Sun, heliosphere, and the terrestrial magnetosphere, ionosphere, and upper atmosphere and the complex interactions among them, solar-terrestrial relations. To advance our understanding in each of these subjects and the chain of interactions among them, a broad scientific attack is necessary, which translates into a major thrust in each of the central disciplines (i.e. solar/space, plasma, and atmospheric physics). In the near term these thrusts are embodied in major space missions—the Solar Optical Telescope (SOT) and the Upper Atmosphere Research Satellite (UARS), already approved, and the International Solar Terrestrial Physics Program (ISTP), currently a new start candidate. These programs together with the base program (research and analysis, mission operations and data analysis, shuttle science, theory, etc.) result in a level of funding of about $400M/yr.*

The important scientific measurement objectives that have been outlined in the previous chapter could add up to a level substantially higher than $400M/yr in the long term. Thus, it was the task of the Committee to establish priorities and to select among the many exciting scientific programs that have been identified, by ordering the sequence of mission implementation within an envelope of about $400M/yr (in FY 85 dollars). The proposed implementation plan contains only those scientific programs that address the highest priority objectives. They are arranged in such a sequence that most would be accomplished before the year 2000. In the process, several programs considered of lesser importance have been deferred (e.g., Heliosphere Boundary Probe), while even those of high scientific priority have had to be scheduled for implementation at a time later than that dictated by either the maturity of the subject or the technological readiness of the proposed measurements [e.g., Solar Terrestrial Observatory (STO)]. In all but two of the programs [the Solar Probe and Solar Polar Orbiter (SPO)] the technology for implementation is already at hand. Thus, the budget ceiling was the determining factor throughout the strategy.

*The funding for solar and space physics in 1964 was $527M/yr (in FY 85 dollars); funding for the decade 1964-1974 averaged $377M/yr (in FY 85 dollars).

Program Mix in Solar and Space Physics

The diversity of environments represented within the discipline of solar and space physics demands a broad mix of programs to implement the stated science objectives. There is a need for major missions for detailed studies on a global scale, as well as for exploration of previously unexamined regions (e.g., the environment near the Sun); for moderate missions (Explorer-class) to attack specific, detailed problems; for quick response techniques such as balloons, rockets (Spartans), and experiments of opportunity best accommodated on the Shuttle; and for facility-class instruments that are developed for Shuttle use but that will evolve towards space platforms that can best be accommodated as part of the Space Station concept.

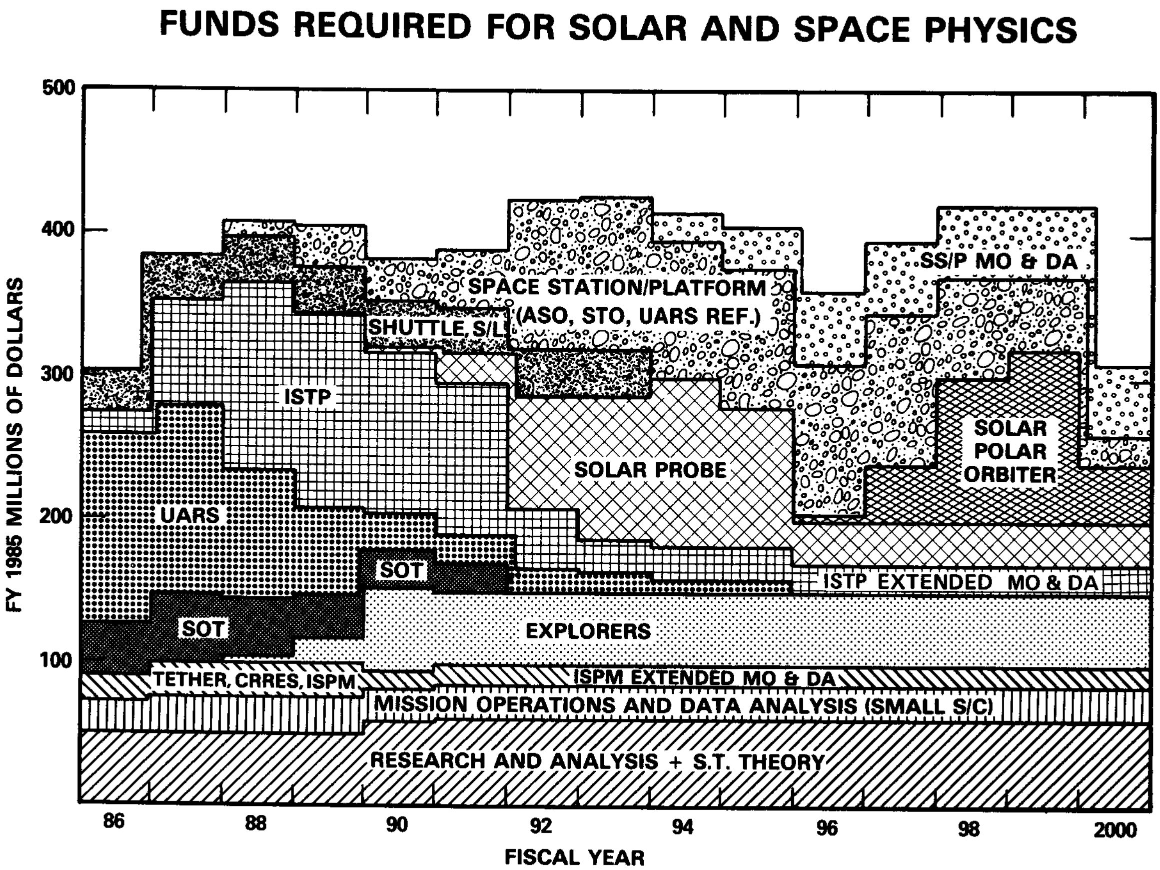


FIGURE 4

Resource Requirements for Recommended Programs

The science priorities outlined in the previous chapter and the rationale in programmatic considerations given above have resulted in an implementation plan with resource requirements over the next 15 years as shown in Figure 4. The total is the sum of three separate budgetary requirements: resources for research and analysis (R&A), for mission operations and data analysis (MO&DA), and for development of flight projects. The R&A budget supports a spectrum of activity including balloons and rockets, laboratory experiments, analysis and interpretation of data from prior spacecraft missions, and the Solar-Terrestrial Theory Program (STTP). The R&A budget additionally includes the resources to plan future missions through the pre-project definition stage and to undertake early development of instrumentation for such missions.

The MO&DA budget pays for the operation of missions after launch [currently Interplanetary Monitoring Platform (IMP)-8; International Sun-Earth Explorer (ISEE) 1, 2, and 3; Solar Maximum Mission (SMM); Solar Mesosphere Explorer (SME); DE; and AMPTE], including science team support and data analysis while the data are proprietary to the selected teams (roughly, one year after acquisition). The budget for development of flight projects supports approved projects through launch and currently includes International Solar Polar Mission (ISPM), Combined Release and Radiation Effects Satellite (CRRES), Tethered Satellite System (TSS), UARS and SOT, and Shuttle instrumentation under various programs.

In the budget projections presented in Figure 4 the Committee has sought to achieve a responsible and attainable funding plan that can be implemented within the funding ceiling outlined previously. This program envisions the launch of the recommended missions before the end of this century. The level of funding for specific programs is primarily based on NASA projections for each of the programs, where such exist, and on informal consultation between the Committee and officials at NASA centers (principally Goddard Space Flight Center, Marshall Space Flight Center, and Jet Propulsion Laboratory) for those programs where such funding levels have not as yet been formalized.

The funding timeline incorporates those programs already approved in FY 85, anticipates implementation of Phase 1 of the ISTP program in FY 86, and foresees utilizing Explorer program funding for solar and space physics following the completion of the current set of payloads by FY 88. The incorporation of the Explorer program into the funding timeline is in accordance with the recent SSB report. *A Strategy for the Explorer Program for Solar and Space Physics* (NAP, 1984).

In the area of Space Shuttle instrumentation, the currently approved program [Spacelab (SL) 1 and 2, Space Plasma Lab (SPL), Earth Observation Missions (EOM), and Sunlab] stays at a constant funding level launched by the year 2000.

In the area of Space Shuttle instrumentation, the currently approved program (Spacelab (SL) 1 and 2, Space Plasma Lab (SPL), Earth Observation Missions (EOM), and Sunlab) stays at a constant funding level through the early 1990s. In the late 1980s, facility-class instruments will be developed, which have been studied previously as part of the Solar Terrestrial Observatory (STO) and the Advanced Solar Observatory (ASO). The instruments will eventually be assembled onto science platforms, which are intended to become part of the Space Station in the mid-1990s. The budget timeline also specifically includes MO&DA funds for the Space Station activity, in recognition of the high cost likely to be involved in operating such facilities.

The solar and space physics programs in Figure 4 are currently managed by several divisions within NASA, including Astrophysics, Earth Science and Applications, Shuttle Payload Engineering, and Solar System Exploration. The Committee has specifically excluded from these budget projections the significant funds that need to be allocated for experiment payloads on planetary spacecraft that are recommended for studies of the magnetospheres and upper atmospheres of the planets. These funds have traditionally been included as part of the overall budget of the specific planetary missions. The budget also does not include specific funds to accommodate possible flights of opportunity that are not currently identified, such as programs of other federal agencies (DOD, NOAA, etc.) or programs arising from international initiatives. A recent example of such a worthwhile opportunity was U.S. instrumentation on the Giotto spacecraft that was accommodated by the overall flexibility of the OSSA budget.

The Committee feels that the program envisioned in this report is scientifically challenging, technologically achievable, and reflects the maturity of a field that was the space research program when the nation initially ventured into space. The implementation plan outlined in Figure 4, by attempting to achieve a constant yearly funding level and distributing the new starts over a number of years, makes it possible for NASA to strive once again for leadership in solar and space physics research.

5 SUMMARY OF RECOMMENDED PROGRAMS

Introduction

In this Chapter we briefly summarize the scientific objectives that were discussed in detail in Chapter 3. These objectives are to be achieved through a sequence of research programs in solar and space physics. We also summarize the descriptions of these programs that are discussed in more detail in Chapters 7, 8, and 9. The primary measurement objectives to be addressed between now and 2000 include the following:

Solar Heliosphere Physics

• High-resolution observations are needed to advance understanding of active regions and the small-scale velocity and magnetic fields important to chromospheric and coronal energy balance, as well as solar flares. These require space-borne instruments that achieve 0.1 arcsec resolution in the spectral range from the infrared to H Lyman alpha and less than 0.5 arcsec resolution from the extreme ultraviolet to hard X rays.

• Remote sensing and in situ measurements are needed to provide qualitatively new information critical to understanding coronal plasma processes and solar-wind generation. These require optical instruments that can make spectroscopic measurements out to 5 or more solar radii and a solar flyby or probe that penetrates as close to the sun as possible (4 solar radii seems technically feasible). In addition, measurements of the heliosphere at high heliographic latitudes are required.

• 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 study (through observations, theory, and modeling) such fundamental problems as magnetic reconnection, particle acceleration, and magnetohydrodynamic (MHD) turbulence; 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 1980s to monitor the effects of solar variability on luminosity over several solar cycles.)

Terrestrial Magnetospheric Physics

To advance quantitative understanding of the time-dependent exchange of energy and plasma between the solar wind and magnetosphere requires measurements of physical processes in at least six regions simultaneously: (1) deep in the Earth's magnetic tail, (2) in the solar wind upstream of Earth, (3) near the mid-magnetosphere equatorial plane, (4) at high altitudes above one polar cap, (5) from the ground, and (6) at low altitude in polar orbit. (Measurement of this last area is needed to indicate the dynamical and chemical response of the atmosphere to magnetospheric variability.)

This global research program should be supplemented with an increased level of support of theory and computer modeling efforts directed toward understanding magnetic reconnection, boundary layer phenomena, and other related problems in magnetospheric physics. In addition, active experiments should be flown that can increase our knowledge of magnetospheric and plasma processes.

Terrestrial Upper-Atmospheric Physics

A series of space observations is needed to advance understanding of the interacting dynamical, chemical, and radiative processes in the stratosphere, mesosphere, and thermosphere. The first in this series is the UARS spacecraft which will provide an almost global data set on the chemistry, dynamics, and energy input of the middle atmosphere to understand basic atmospheric properties and processes. Thereafter solar-terrestrial processes should be addressed by remote sensing of the chemical, dynamical, and thermal response of the mesosphere and lower thermosphere to solar and magnetospheric perturbations. Continuing upper-atmospheric observations throughout the 1990s are needed to provide good solar-cycle coverage. Complementary high-resolution studies should be made using Shuttle facilities.

Evolution of Shuttle Science

It is essential to maintain a strong program for the development and flight of Shuttle-class instruments in solar, atmospheric, and magnetospheric physics. Continued progress in solar-terrestrial physics requires innovative new measurements. The Shuttle provides an excellent platform for the flight of many types of solar-terrestrial instruments and acquisition of short duration (up to a week or more) measurements of specific phenomena. Shuttle experiments can include both in situ and remote observations of natural phenomena and diagnostics of active perturbations of the plasma medium with chemicals, waves and electron or energetic plasma beams.

Ultimately Shuttle instruments can be used on the Space Station, which combines the greatest advantages of the Shuttle and smaller spacecraft, namely high resolution and long duration.

Theory, Computer Modeling, and Information Handling

The ultimate goals of the solar and space physics scientific missions are the resolution of outstanding scientific questions and the creation of reliable predictive models of the solar-terrestrial environment. Critical to achieving these goals is conversion of the observations into scientific understanding through a strong theoretical and computer modeling program. This process leads to the resolution of outstanding questions and the formulation of new ones, which in their turn lead to the formulation of new missions; it also leads to the gradual building of reliable, predictive, cause and effect models of the solar-terrestrial environment. A strong theoretical and computer modeling program is a cornerstone for successful solar and space physics research. Moreover, theory and quantitative modeling can guide the entire information chain (data acquisition, reduction, dissemination, correlation, storage, and retrieval) to a higher level of sophistication, so that data can be made available in a form compatible with the needs of scientific interpretation.

Coordinated Research

Coordinated research is an essential feature of solar and space physics, which is concerned with time-variable phenomena spanning several regions of space and relying on several scientific disciplines for interpretation.

The research programs proposed above are justifiable on their individual merits. Coordinating them through the ISTP can greatly increase our understanding of the solar-terrestrial interaction. Examples of such coordinated research include the following.

(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 International Solar Polar Mission (ISPM) spacecraft.

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

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

The NASA research proposed here provides a foundation for coordination of research sponsored by other agencies of the United States government and possibly foreign nations. For example, coordination with other agencies is critical to provide the ground-based observations recommended above. We urge that NASA play a prominent role in developing and coordinating a joint program as rapidly as possible.

Planetary Research

Since we 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 the impact on space 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 many members of the space physics community also work 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. Therefore, measurements of plasmas, fields, and energetic particles must remain integral parts of each planetary mission.

Major Missions

Solar and Heliosphere Physics

The Solar Optical Telescope

The first approved facility-class instrument under development in the Spacelab program is the Solar Optical Telescope (SOT). SOT consists of a 1.25-m aperture telescope with 0.1-arcsec resolution, which will provide sufficient resolution to observe levels in the solar atmosphere ranging from the photosphere through the transition region. The critical problems to be studied include plasma-magnetic field interactions related to the solar dynamo and studies of energy transport in the solar atmosphere.

SOT will be flown as an attached Shuttle payload at intervals of 1 to 2 years starting in 1990. The program is expected to evolve with the addition of increasingly versatile focal-plane instrumentation and other complementary experiments. Eventually, SOT would form the basis for an advanced solar observatory on a space station platform.

Solar Probe

The Solar Probe is a mission to study the unexplored region between about 4 and 60 solar radii from the Sun. The basic scientific goal is to explore the solar atmosphere where the solar wind becomes supersonic. The mission should carry a complement of particle and field instruments to measure density, velocity, and composition of the thermal solar wind plasma, as well as the magnetic fields, plasma waves, and energetic particles present in this unexplored region of the heliosphere.

Solar Polar Orbiter

The study of the three-dimensional properties of the heliosphere will require observations more detailed than those that will be obtained by the ISPM, the first exploratory mission to high solar latitudes. A Solar Polar Orbiter (SPO) in near circular orbit about the solar poles, at heliocentric distance less than or equal to 1 AU, will be able to distinguish latitude from radial variations and, since it will make several polar passes, to distinguish spatial from temporal effects. SPO should carry a full complement of plasma, energetic particle, magnetic field, and radio wave instruments, similar to those flown on ISPM, and should have pointing capability for detailed solar and coronal observations. The mission will require the development of low-thrust, continuous acceleration propulsion. Mission design for SPO should be undertaken in the mid-1990s, following a thorough analysis of the results of ISPM; launch should occur by the year 2000.

Plasma Physics

International Solar-Terrestrial Physics Program

The International Solar-Terrestrial Physics Program (ISTP) is being planned together by the U.S. NASA, the Japanese Institute of Space and Astronautical Science (ISAS), and the European Space Agency (ESA) as a cooperative effort with launches beginning in 1989 and with operations continuing into the mid-1990s. The overall scientific objectives of ISTP are to develop a comprehensive, global understanding of the generation and flow of energy from the Sun, through the interplanetary medium and into the Earth's space environment (geospace), and to define the cause-and-effect relationships between the physical processes that link different regions of this dynamic environment.

ISTP will provide complementary measurements for several other spacecraft, Shuttle/Spacelab missions, sub-orbital and ground-based investigations that are being conducted in the same time interval. Plans include coordinated operations and data interpretation with at least the ISPM, the Japanese Exospheric Satellite-D (EXOS-D), the Upper Atmosphere Research Satellite (UARS), Shuttle/Space Plasma Lab, and Shuttle/Sunlab.

Six spacecraft missions are being planned for ISTP; spacecraft characteristics are described as follows:

WIND, provided by NASA, will have seven instruments to measure the solar wind magnetic field, plasma, plasma wave, and energetic particle characteristics; the orbit is a double lunar swingby with excursions of 250 R_E into the upstream solar wind.

GEOTAIL, provided by ISAS, will have seven instruments to measure the magnetic and electric fields, the plasma energy and composition, and the plasma waves in various regions of the geotail; the orbit initially is to be a double lunar swingby out to 250 R_E in the geotail, to decrease to 8 $R_E \times 20\ R_E$ in the equatorial plane.

POLAR, provided by NASA, will have eleven instruments to make comprehensive in situ measurements of the plasma, fields, energy, composition, and waves with the added capability to image the Earth at x-ray, ultraviolet and visible wavelengths from a polar orbit of 1.5 $R_E \times 8.5\ R_E$.

EQUATOR, provided by NASA, will carry nine instruments to fully characterize the plasma, fields, energy, composition, and waves in the equatorial region at an orbit of 2 $R_E \times 12\ R_E$.

SOHO, provided by ESA with nine telescopic instruments to measure the solar surface and solar corona over a wide range of wavelengths and five solar wind instruments to measure fields, plasma characteristics, and plasma wave emissions, will be stationed at the L_1 Lagrangian point and will be three-axis stabilized.

CLUSTER, provided by ESA, will include four Explorer-class spacecraft, each with about six instruments to carry out spatially separated (100 km − 20,000 km) measurements of magnetic fields, plasma waves, energetic and thermal particle distributions, and plasma composition in an effort to explore turbulent boundary-layer phenomena in the magnetosphere and magnetohydrodynamic turbulence in the solar wind. The orbit is polar, 3 $R_E \times 20\ R_E$.

The first four spacecraft make up the elements of the first ISTP phase with launches planned for 1989–1991 called the Global Geospace Study (GGS). GGS will focus on the global flow of energy from the solar wind through the magnetosphere to the ionosphere and into the atmosphere. The processes by which different parts of the geospace environment interact are highly variable with time, often changing in response to fluctuations in the characteristics of the solar wind on the time scale of tens of minutes. Thus, the key to success for GGS is in making simultaneous measurements in the four regions in which these four spacecraft orbit.

The two ESA spacecraft systems (CLUSTER and SOHO) are planned for launch in 1992–1993. Each system makes a unique contribution to the overall science program. CLUSTER consists of four spacecraft with adjustable separations designed to make cross-correlative measurements of plasma characteristics and processes within the volume defined by the four spacecraft set. These measurements provide information on the nature of the microscopic plasma processes that occur near boundary layers in the magnetosphere. The use of 4 spacecraft will enable the separation of spatial and temporal effects. When in the solar wind, the spatial resolution made possible by the four spacecraft will significantly enhance studies of MHD turbulence.

SOHO performs three types of measurements: observations of global oscillations to deduce information about the solar interior, the solar corona including both long-term variations and transient features of the solar corona through both imagery and spectroscopy, and in situ solar wind characteristics. SOHO provides the relation between solar variations and resulting phenomena in the solar wind and observed in the magnetosphere with the GGS spacecraft.

An essential element of the ISTP program is a coordinated data analysis and archival system that will facilitate effective interaction by the participating community of investigators who will interpret the ISTP and associated data bases.

The collaborative ISTP Program will bring a broad international science community together with enhanced opportunities for scientific accomplishments through an integrated attack on the problems of solar-terrestrial relations, magnetospheric physics, space plasma physics, and solar physics.

Upper-Atmosphere Physics

The highest priority in observatory-class missions for the 1980's has been UARS, now a new start in FY 85. UARS is the spacecraft recommended in the Kennel report and will provide for the first time an almost global data set on the chemistry, dynamics, and energy inputs of the 10-70 km region of the atmosphere, i.e., the stratosphere and lower mesosphere. The goals of the UARS program are to understand the mechanisms controlling middle atmospheric structure and processes and to understand the response of the upper atmosphere to natural and human perturbations. The UARS data will be critical elements in evaluating the extent of ozone depletion caused by human activities and the role of upper atmosphere processes in climate change. The instrument payload has been carefully selected to meet the goal of coordinated and complementary global measurements of ozone, temperature, pressure, energy input, winds, and chemical trace species by remote sensing. The UARS program includes theoretical studies and model analysis as an integral part of the program to complement the measurements and data analysis.

Explorers

Explorers have played a crucial role in the development of solar and space physics research, and we see their role continuing in the future. The primary role of Explorer missions is to attack well-defined scientific problems of high current interest in a timely fashion. Explorers may also be used productively in conjunction with the global programs required by solar and space physics research, as identified in "Major Missions" above.

The basic strategy for use of the Explorer program in solar and space physics is contained in a recent NAS report (*A Strategy for the Explorer Program for Solar and Space Physics*, NAS, 1984). The recommendations of that report are as follows:

1. The size, complexity, and management of future Explorer missions should return to the originally perceived philosophy of the Explorer program (i.e., relatively small, simple satellites) and should be designed to address focused problems in a timely manner.

2. Scientific opportunities for solar and space physics research merit an average of approximately one Explorer satellite opportunity a year in the future. If an average of one launch per year is not feasible with current funding, the Explorer budget should be augmented.

3. An Announcement of Opportunity (AO) mechanism and selection process should be used to identify approximately twice the number of solar and space physics Explorers that can be expected to be flown in the time interval between AOs. Further, the selection process should be conducted in two stages in order to reduce the amount of time and effort expended by the science community. The first stage would be a selection for definition studies, the second stage a selection for development.

These recommendations have been incorporated in the funding timeline shown in Figure 4, with a flight frequency of about one launch per year, to be shared as appropriate by solar/heliospheric, magnetospheric, and upper atmosphere missions.

Spacelab/Space Station Payload Evolution

Initial utilization of the Space Shuttle in 1982–1985 for solar and space plasma physics investigations is through the OSS-1, Spacelab-1, and Spacelab-2 missions. Missions to follow in the 1986–1990 interval include Sunlab, Space Plasma Lab, Tether, and SOT. Instruments and investigation techniques developed for these Shuttle missions form the basis for two solar and space physics facilities on the Space Station—the Advanced Solar Observatory (ASO) and the Solar-Terrestrial Observatory (STO).

The early Shuttle/Spacelab missions will carry solar instruments to measure the total solar irradiance variation on short and long time scales and instruments to measure the emission spectra, the magnetic field configuration, and the spatial patterns of solar active regions. These and additional instruments are to be re-flown in a series of Sunlab missions. Derivatives of these instruments will be developed to become part of the ASO.

The early Shuttle/Spacelab space plasma missions have emphasized active space plasma experiments utilizing electron beam and energetic plasma sources. These sources perturb the plasma in the immediate vicinity of the orbiter as well as along magnetic field lines leading to optical emissions, energetic particles, and electrostatic waves. The perturbations are observed remotely with optical telescopes, spectrometers, and wave receivers as well as in situ through plasma diagnostics packages. These plasma perturbation and diagnostics instruments will become part of the Space Plasma Lab instrumentation which will have, in addition, a VLF and HF wave generation system. In the Space Station time frame, the Space Plasma Lab instruments should become part of the STO for the conduct of active experiments and for monitoring the Space Station plasma environment. The STO is also to include instruments for viewing the Sun and the Earth's atmosphere to provide cause-and-effect measurements of the Sun-Earth interactions as well as measurements of the chemistry, dynamics, and energies of the middle and upper atmosphere.

In 1987 the Tether Satellite System (TSS) will be initiated to tether a diagnostic satellite 20 km above the Shuttle. With a conducting tether, the system can be utilized to excite long-wavelength, low-frequency waves, create controlled plasma wakes and alter the electrodynamics of the ionospheric medium. With a non-conducting downward tether, it becomes possible to drag an atmospheric satellite at 130 km altitude—a region previously inaccessible on a global scale. The TSS will be implemented on the Space Station to extend the investigation periods.

SOT is designed to measure 0.1-arcsec scale features of the solar surface in the visible light range to investigate small scale convective patterns. After the maiden flight in about 1990, the SOT will be outfitted with co-observing instruments in the x-ray and extreme ultraviolet wavelength ranges to examine the range of processes on the 0.1-arcsec spatial scale. The SOT and its co-observing instruments will become the core of the ASO on the Space Station. Also, a Pinhole Occulter Facility (POF) will be added so that hard x rays produced by energetic electrons accelerated in solar flares and other transient phenomena can be imaged on the sub-arcsec scale and so that the solar corona can be imaged and analyzed over a wide wavelength range. Eventually, instruments can be added to the ASO to measure the variability in solar irradiance, solar energetic particles, and gamma ray emissions.

Suborbital Program

Suborbital programs employing balloons, rockets, and aircraft provide an important and, in some cases, unique platform for certain scientific investigations. For example, the effects of solar cosmic rays on atmospheric composition represent a form of solar-terrestrial coupling that can be most directly observed in situ using rockets and balloons. Such observations would include simultaneous in situ measurements of the high energy particle and bremsstrahlung spectra of NO_x, O_3, and other related minor constituents. Similarly, determination of the ion composition of the ionosphere below about 120 km can probably be most effectively performed with in situ instruments.

Suborbital platforms are also valuable in the development and testing of future spacecraft instrumentation in a relatively inexpensive and timely fashion, can serve to provide "ground truth" for atmospheric remote sensing measurements, and often can provide data on much finer spatial and temporal scales than those presently achievable by remote sensors.

Rocketborne payloads also offer frequent and flexible flight opportunities for the increased quantities of "active experiments" in atmospheric science. Experiments that require waiting for appropriate geophysical conditions cannot be easily accommodated using Spartan- or Shuttle-type orbiting payloads. An additional aspect of the suborbital program is the important opportunities it offers to graduate training by providing complete formulation to data analysis experience in space science programs.

Theory and Computer Modeling

The disciplines in solar and space physics are seeking quantitative understanding of the relevant physical processes. The interplay between theory and experiment, coupled with the tool of computer simulations, is proving invaluable in advancing this understanding. Theory provides the mechanisms for unifying laboratory, space, and astrophysical plasma physics.

The Colgate report (*Space Plasma Physics: The Study of Solar System Plasmas*, NAS, 1978) identified the need for adequate theoretical studies in solar and space plasma physics. In response, NASA established in 1980 the Solar Terrestrial Theory Program (STTP) to fund "critical mass" theoretical groups in the major discipline areas and to provide stable career opportunities to younger theoreticians. The STTP has been highly successful; groups have been established that are providing major new insights into critical problems such as reconnection, collisionless shock structure, particle acceleration, and radio emission processes. The STTP is now contributing to basic laboratory plasma physics and to a better understanding and interpretation of numerous space data sets. A summary of much of this research is described in *Solar-Terrestrial Physics—Present and Future*, ed. D. Butler and K. Papadopoulos, 1984, which also includes descriptions of theoretical research sponsored by NSF and NASA under other programs.

Funding for STTP is currently at $3.3 million in FY 85. Substantial increases in this program would provide growth opportunities for established groups and allow for new entries. A level of about $6 million (in FY 85 dollars) to be achieved by FY 90 will provide the appropriate balance between theory and the experimental program.

NASA has also recognized the need for theoretical groups to participate in a principal investigator (PI) role in NASA missions. This offers the possibility of establishing closer quantitative links between mission planning, data analysis, and theoretical and computational modeling than has heretofore been possible. DE, UARS, ISTP, and Combined Release and Radiation Effects Satellite (CRRES) are examples with theoretical PI participation. We recommend that the policy of theoretical PI team participation be continued in solar and space physics and in planetary investigations.

Although many theoretical problems in solar and space physics can be addressed with currently available computers, many problems (especially related to solar dynamics, MHD turbulence, and ISTP related issues) will require availability of supercomputers, supported by high data rate telephone or microwave links to researchers, as well as enhancements of local computer processing facilities. A firm NASA commitment to advanced computer facilities dedicated to atmospheric and plasma physics modeling is of critical importance. We concur with the recommendation in the Physics Survey Report for a National Computational Program that proposes a large-scale theoretical modeling and simulation effort for basic plasma physics, space physics, and astrophysics.

Mission Operations and Data Analysis

The MO&DA program is vitally important to NASA's space research mission. It is through this program that the *scientific* return from space experiments is finally realized; MO&DA funding supports the experiment operations, provides (sometimes) for extended missions, and is responsible for the processing and analysis of the data.

Currently operating spacecraft are a national resource and frequently provide unique opportunities for gathering scientific information. For example, Interplanetary Monitoring Platform-8 (IMP-8) is the only spacecraft that can provide information on solar wind parameters at the present time. The Pioneer Venus Orbiter has been providing unique and invaluable information on the solar wind-ionosphere-atmosphere interaction processes; its continuously rising periapsis is allowing measurements to be made in new and unexplored regions of the Venus plasma environment. The International Comet Explorer (ICE) mission will explore a comet tail for the first time in September, 1985, and provide essential measurements of solar wind parameters upstream from Halley during its perihelion passage in 1986. Furthermore, the deep space missions of Pioneers 10 and 11 and Voyagers 1 and 2 provide the only means of studying the global properties of the heliosphere at large distances from the Sun. Thus, it is important for NASA to continue MO&DA funding for existing spacecraft and for "cruise mode" measurements by planetary spacecraft.

Historically, NASA has not adequately funded its MO&DA needs. Since MO&DA is a critical element of all NASA's science programs, care must be taken to ensure that it not be neglected as large programs occupy increasing attention and funding commitments.

In Chapters 7, 8, and 9 of this report, examples of MO&DA needs are specified and recommendations for increased funding are made.

Research and Analysis

A strong research and analysis program is the essential foundation for the entire science program. Its vital elements include the following:

1. the theory and analysis essential for assessing the state of the field, for combining and interpreting the results of the various flight projects into a self-consistent body of physical knowledge, for transfer of new results to and from the fields of laboratory plasmas and astrophysics, and for planning future research;
2. development of instruments for future flight projects;
3. correlative observations that enhance the scientific return from the space flight projects; and
4. supporting or complementary research performed in laboratories or with suborbital flight programs.

Another important function of the R&A program is to provide the long-term stability required to maintain the scientific capability of research groups through the lean years between major flight projects.

In Chapters 7, 8, and 9 of this report, we review the R&A programs in each of the main disciplines of solar and space physics, and we recommend areas within the R&A program where increased funding is required.

Technology Requirements and Instrument Development

All of the missions recommended for the 1980s and most of the missions recommended for the 1990s can be implemented with existing spacecraft technology. The exceptions are the requirement for a low-ablation heat shield for the Solar Probe and advanced propulsion (probably solar-electric powered ion thrusters) for the SPO. If it were available in time, advanced propulsion could also be used to enhance the Solar Probe mission by achieving a shorter period solar orbit. We recommend that NASA proceed with these developments to meet the planned new start dates of 1991 and 1997 for the Solar Probe and the SPO, respectively.

The development of scientific instruments is now and should continue to be a high-priority effort. Major emphasis should be placed on the development of (1) PI-class and facility instruments for solar observations, leading ultimately to the ASO; (2) imaging instruments to remotely sense the hot plasma processes in the magnetosphere; and (3) post-UARS instruments for detection of a greater number of chemical species in the upper atmosphere, particularly important free radicals such as OH and HO_2 along with ozone, solar irradiance, and temperature. For all the missions later in our implementation plan, many instruments should be enhanced by taking advantage of new technologies such as better detector arrays, cryogenic systems for sensor cooling, microprocessors, data storage devices, and software to process and compress data on board the spacecraft. Chapters 7, 8, and 9 specify the technology requirements for each of our main disciplines.

6 SCIENCE HIGHLIGHTS AND ACCOMPLISHMENTS

This Chapter is a brief review of some of the most significant scientific accomplishments of several past research programs. We include it in this report to demonstrate the important contributions to our understanding of the Earth's environment and the basic physical processes of the universe that have resulted from research activity in this area.

Skylab

Skylab, with its battery of solar telescopes in the Apollo Telescope Mount, was launched in May 1973 and was operated by three crews until February 1974. Eight instruments, including two x-ray telescopes, an EUV spectroheliograph, a uv spectroheliometer, a uv spectrograph, a visible-light coronagraph, and H-alpha telescopes, studied the Sun over the wavelength range 2-7000 Å. Principal scientific results included the following:

- recognition of the highly inhomogenous structure of the corona and the close correlation between coronal radiation and magnetic field structure, finding that over most of the surface the elemental structures are magnetic arches or loops connecting regions of opposite magnetic polarity (This along with the Skylab observations of coronal holes revolutionized our concepts about the structure of stellar coronae.);
- confirmation that coronal holes are sources of recurrent high-speed solar wind streams, resolving a long-standing problem on the solar origin of these streams and leading to major revisions in models of the solar wind at its coronal source;
- discovery of transient mass ejections from the corona at an unexpected high rate and an unexpected large scale, significantly revising concepts about the role of transient phenomena in the energetics and evolution of the corona;
- discovery of hot, x-ray emitting magnetic loops associated with flares and the discovery that a substantial fraction (often greater than 50 percent) of the energy associated with large flares is carried away from the Sun by coronal mass ejections—observations that led to improved knowledge of the energetics of flares and the relationships between the diverse phenomena observed during flares;
- discovery of nearly random spatial distribution of coronal x-ray bright points identified with small magnetic bipoles and the discovery of rapid temporal variations in the emission from these features, providing insights concerning the emergence of magnetic flux from below the surface and the role of magnetic field dissipation in heating the coronal plasma; and
- discovery of rapid, large amplitude fluctuations in solar extreme ultraviolet (EUV) flux, but without evidence for an expected periodic component, providing evidence that the corona is not heated by periodic waves as predicted in some theoretical models.

P78-1

The P78-1 spacecraft is part of the DOD Space Test Program and was launched by the Air Force on 24 February 1979. The satellite was built with assistance from NASA, which provided the stabilization and solar pointing control systems and other flight space components from NASA's seventh Orbiting Solar Observatory (OSO). Solar instrumentation includes a white-light coronagraph, soft x-ray Bragg crystal spectrometers, and hard x-ray proportional counters. Some scientific results are as follows:

- first observation of earth-directed coronal transients, i.e., "halo" transients, demonstrating that at least some transients are bubble, rather loop-like, in shape;
- the accumulation of a data base for outer coronal activity that extends from 1979 until September 1985, producing many statistical results, e.g., on average two coronal mass ejections occurred per day during the years 1979-1981 near sunspot maximum;
- the discovery that greater than 75 percent of the interplanetary shocks observed

by the Helios spacecraft originated with coronal mass ejections;

• the discovery of four sungrazing comets, none of which were seen after perhelion, implying either destruction by the solar atmosphere, or actual impact into the photosphere;

• the first accurate determination of the temperature of the bulk of the soft x-ray emitting thermal flare plasma;

• the discovery that 300-500 km s^{-1} upflows at temperatures of about 15 x 10^6 K are a common occurrence during the rise phase of large solar flares;

• the first systematic study of the time behavior of random mass motions in soft x-ray flare plasmas; and

• the discovery of high density ($\simeq 10^{12}$ cm^{-3}) coronal plasma ($\simeq 2 \times 10^6$ K) of very small volume ($\simeq 10^9$ km^3), produced coincident with the hard x-ray flare impulsive component.

Solar Maximum Mission

The Solar Maximum Mission (SMM) was launched in February 1980 and repaired on-orbit in 1984. It is dedicated to coordinated observations of specific solar activity and solar flare problems. The payload contains seven instruments, including an Active Cavity Irradiance Monitor, a coronagraph, and several imagers and/or spectrometers covering the spectrum from uv to gamma rays. Some of the most significant results include the following:

• accurately measured changes in solar irradiance associated with solar activity, suggesting the probability of transient energy storage inside the Sun;

• discovery of near temporal coincidence of gamma rays produced by energetic ions and of hard x rays produced by energetic electrons at times of solar flares, providing constraints on the energy release mechanisms in flares;

• discovery of frequent occurrence of small flares producing hard x-ray and EUV radiation, indicating powerful energy releases on scales smaller than previously known;

• discovery of hard x-ray and EUV sources at the foot points of coronal loops, providing strong evidence for the thick-target model of x-ray production; and

• discovery of large-scale circulation patterns in the chromosphere and low corona in active regions, suggesting a solution of mass conservation dilemmas indicated by earlier observations.

Orbiting Solar Observatory-8

The Orbiting Solar Observatory-8 (OSO-8) was launched in June 1975, as the last of a series of satellites intended to study the Sun through a solar cycle and to map the entire sky in ultra violet, x-ray, and gamma-ray radiation. Some important results include the following:

• demonstration that the energy flux in sound waves at the top of the chromosphere is too low to explain coronal heating and

• verification of widespread down-flow in the chromosphere-corona transition region.

Heliosphere Missions

Several missions have been valuable in exploring the heliosphere.

• Pioneer 10 and 11, the first experiments to the outer solar system (launched in March 1972 and April 1973, respectively), performed flybys of Jupiter and Saturn and conducted studies of planetary and interplanetary magnetic fields, solar wind parameters, cosmic rays, transition region of the heliosphere, neutral hydrogen abundance, and properties of dust particles.

• Voyager 1 and 2, launched in September 1977 and August 1977, respectively, studied Jupiter and Saturn as well as the interplanetary medium.

• The Interplanetary Monitoring Platforms (IMP) series of missions carried out studies of interplanetary space and the Earth's magnetosphere. The last of the series, IMP-8, was launched in September 1972.

• Helios, developed by the FRG in cooperation with NASA, was a two-spacecraft mission, launched in December 1974 and January 1976. The purpose of the mission was to study the interplanetary medium between 0.3 and 1 AU.

Some scientific results include the following:

• discovery that the interplanetary sector structure is the ecliptic plane projection of a three-dimensional heliospheric current sheet (Pioneer 11);

• tracking of type III solar radio bursts to Earth orbit [Simultaneous measurements of plasma waves, radio waves, and energetic electrons (IMP 6) provided a global view of the three-dimensional structure of the interplanetary magnetic field.];

• studies of three-dimensional MHD turbulence in the solar wind beyond 1 AU using magnetic field and three-dimensional plasma data (Voyagers 1 and 2) —first determination of the three global invariants of incompressible, three-dimensional MHD turbulence; and

• discovery that coronal holes are the source of high-speed solar wind streams (Helios, Skylab).

International Sun-Earth Explorer

The International Sun-Earth Explorer (ISEE) was a three-spacecraft mission, with launches in October 1977 (ISEE-1 and -2) and August 1978 (ISEE-3), to investigate solar-terrestrial relationships near the boundaries of the Earth's magnetosphere, the solar wind near the Earth's bow shock, cosmic rays, and solar flares in the interplanetary region near 1 AU. ISEE-3 was moved, in June 1982, from its halo orbit in the solar wind to make several excursions into the far magnetotail (1983) and was then directed into a trajectory that will intercept the tail of comet Giacobini-Zinner in September 1985. The significant results to date include the following:

• mapping the structure and fundamental physics of the Earth's bow shock and upstream region (ISEE-1,2);

• demonstration of steady-state reconnection at dayside magnetopause, thus showing the operation of a physical process that had long been predicted theoretically and inferred from global magnetospheric observations (ISEE-1,2);

• discovery and characterization of transient reconnection (flux transfer events) at dayside magnetopause (ISEE-1,2), showing the dynamical importance of a more "patchy" kind of energy transfer between the solar wind and magnetosphere;

• measurement of magnetopause wave structure and motions (ISEE-1,2), showing that the magnetopause is a highly complex and dynamic region as opposed to the simple laminar region often pictured in models;

• extension of ion composition measurements to high altitudes, demonstrating both ionospheric and solar wind plasma sources (ISEE-1,2);

• electric field measurements throughout terrestrial magnetosphere and environs (ISEE-1,2) (Since electric fields are the causal agents of particle acceleration and they effect plasma transfer, the successful measurement of electric fields represents an important advance in observational techniques.);

• improved observations of reconnection in magnetotail, including detailed structure of plasma sheet (ISEE-1,2,3) (Reconnection processes appear to be very important both for the quiet time structure of the plasma sheet and for the temporal evolution of the magnetotail structure during substorms.);

• demonstration of the importance of single particle motion within boundary regions of the plasma sheet (ISEE-1,2);

• continuous monitoring of solar wind input functions from upstream libration point providing critical information about the solar wind electromagnetic fields that "drive" geomagnetic activity (ISEE-3);

• first detailed survey of distant tail showing the structure, evolution, and dynamics of the region beyond the lunar orbit (ISEE-3);

• confirmation of plasmoid formation and escape from magnetotail during substorms (ISEE-3) (Such plasmoids carry away very large amounts of mass and energy from the near-Earth tail and represent a major form of dissipation as the magnetosphere returns toward a "ground-state" after substorms.); and

• first high-resolution measurements of the isotopic composition of solar flare and galactic cosmic ray nuclei, thus advancing our understanding of cosmic-ray acceleration and propagation processes (ISEE-3).

Dynamics Explorer

Dynamics Explorer (DE), launched in August 1981, was a two-spacecraft mission designed to study the strong interactive processes coupling the Earth's magnetosphere and ionosphere. The spacecraft were placed in polar orbits to permit simultaneous measurements at high and low altitudes on the same field lines. Significant results to date include the following:

• first global images of auroral oval and polar cap showing substorm evolution;

• strong coupling between convectively driven ions and the neutral atmosphere, implying an important form of energy and momentum coupling at ionospheric altitudes;

• a new relationship between the convection electric field and field-aligned currents and interpretation of this in terms of the mechanism for driving the magnetospheric-ionospheric coupling currents;

• first observation of postulated non-thermal line profiles of oxygen in the nighttime thermosphere;

• neutral winds of very high speed (approximately 1500 km/hr)—over twice maximum speed observed during the Atmospheric Explorer (AE) mission—implying great variability of the upper atmospheric wind system;

• polar wind at high latitudes, which, predicted theoretically, demonstrates that the polar ionosphere is an extensive source of magnetospheric plasma during magnetic storms;

• nitrogen ions in the magnetospheric plasma, clearly of low ionospheric origin and previously unobserved;

• correlated magnetic and electric field variations that provide remote sensing of ionospheric current and conductivity, which determine, in significant measure, the levels of energy dissipation in the ionosphere;

• first global scale mapping of thermospheric winds and temperatures that showed neutral atmospheric circulation patterns (In particular, the mission confirmed that ion drag is a dominant force on high latitude neutral atmosphere in polar regions.);

• first measurement of height of auroral hiss emission region; and

• frequent occurrence of extremely high densities of field-aligned currents, suggesting a "clumping" and localization of current patterns rather than broad, uniform distribution over large polar regions.

Shuttle/Spacelab—Space Plasma Physics

• Electron beam and plasma emitters successfully operated on the Shuttle without any significant charging. There is evidence for strong beam-plasma interactions with particle energization and generation of intense electrostatic waves.

• In most cases, the onset of plasma energization and anomalous ionization limited charging to below 100V. In one case, kV charging was detected. The preliminary explanation for this is inaccessibility of the conducting areas to the plasma energized by the beam injection.

• Discovery of the "Shuttle Glow" and its correlation with electrostatic wave and particle energization phenomena caused by collective plasma interactions may support a plasma hypothesis for this phenomena.

• Major enhancement in ionization when N_2 was released in the "ram" direction from the Shuttle, may be similar to "Critical Ionization" although the speed of the release was subcritical.

Planetary Magnetosphere/ Atmosphere Missions

The Pioneer and Voyager missions were described in the section on Heliosphere Missions. The significant results of their investigations of the magnetospheres and atmospheres of Jupiter and Saturn include the following.

• Jupiter is the dominant source of 1-40 MeV cosmic-ray electrons in the heliosphere.

• Jupiter's magnetosphere is the largest object in the solar system, 10 solar diameters in width, with an identifiable tail that extends at least beyond the orbit of Saturn (Pioneer 10 and 11 and Voyager 1 and 2).

• Jupiter's moon, Io, serves as a source of heavy ions that form a torus surrounding Io's orbit in the inner magnetosphere. Ions from the torus are accelerated to relatively high energies (tens of keV) and are found throughout the magnetosphere (Voyager 1 and 2) at extremely high temperatures (about 3×10^8K). Because of Io's plasma torus, radio emissions from Jupiter's ionosphere and magnetosphere reveal a complex pattern in frequency and space unanticipated from ground-based observations (Voyager 1 and 2).

• Saturn's magnetosphere is intermediate in structure between Earth's and Jupiter's, both in scale and in importance of centrifugal distortion. Internal plasma sources include the atmosphere, moons, and rings, which serve as sources of both protons and heavy ions (Pioneer 11, Voyager 1 and 2).

• Radio emissions from Saturn define a stable rotational period, but the intrinsic magnetic field is symmetric about the rotation axis, so the cause of the modulated emissions is not established (Voyager 1 and 2).

• Elongated radial features ("spokes") are found in the B-ring near the orbit synchronous with planetary rotation, and are best understood by invoking charged dust grains electrostatically coupled to local plasmas (Voyager 1 and 2).

• Saturn's atmospheric structure is similar to Jupiter's, but equatorial wind speeds up to 1500 km/hr are four to five times faster than those on Jupiter (Voyager 1 and 2).

• Titan's exosphere generates strong EUV emission by magnetospheric interactions (Voyager 1 and 2). This interaction is important in the evolution of Titan's atmosphere.

Atmosphere Explorers

The Atmosphere Explorer (AE) series of spacecraft were designed to study the Earth's upper atmosphere. The last of the series was launched in November 1975. The principal results include the following:

• comprehensive measurements and understanding of the ion and neutral photochemistry of the thermosphere and inference of various reaction rate coefficients, which led to the solution of outstanding photochemical problems of the thermosphere;

• detailed measurements of the diurnal, latitudinal, longitudinal, and seasonal variation of the neutral constituent concentrations in the thermosphere, which indicate the importance of solar and geomagnetic activity on the thermosphere;

• in-situ measurements of vertical velocities, kinetic temperature, and interhemisphere transport induced by neutral meridional winds that provided a firm basis for understanding compositional changes in the thermosphere;

• direct measurements of the winter helium and hydrogen bulges, demonstrating the importance of transport by interhemispheric wind systems;

• high resolution, low energy particle measurements of the daytime photoelectron spectra, electron spectra in the high latitude ionosphere and quiet dayside cusp that provided accurate electron impact emission rates of auroral and airglow features that are diagnostic of energy input to the thermosphere;

• measurements of solar wind plasma injection in the dayside cusp, of convection in dayside auroral arcs, of polar cap electron acceleration regions and substorm effects on the auroral plasma that provided important data to understand magnetosphere-ionosphere coupling; and

• detailed in-situ measurements of plasma bubbles and irregularities in the equatorial ionosphere, which are important signatures of plasma instabilities in the F region.

Nimbus-7

The Nimbus-7 Satellite, which is the last in the Nimbus series, was launched October 24, 1978, for the purpose of sounding the oceans, Earth radiation budget, and the middle atmosphere. Four experiments were dedicated to study of the middle atmosphere, three of which were limb sounders (LIMS, SAMS, and SAM II) and the fourth, the SBUV experiment, used nadir backscattered ultraviolet radiation. A collective summary of middle atmosphere scientific results is as follows:

• Provided first global distributions of H_2O, NO_2, HNO_3, N_2O, and CH_4 showing latitudinal gradients, significant variability, seasonal changes, and important new challenges to theory. Concurrent observations of CH_4 and H_2O provide a unique opportunity to study the production of H_2O through the tropical tropopause.

• Produced first experimental evidence of downward transport of NO_x from high altitudes to the mesosphere and upper stratosphere in high latitude winter providing detailed observations for comparison with theoretical results, for study of impact on the NO_x budget in the stratosphere, and for analysis of photochemical time constants, vertical velocity, and lower mesosphere wave activity.

• Provided detailed observations of rapid NO_2 decreases with latitude at high winter latitudes in the stratosphere (the NO_2 "cliff") and showed importance of including interaction between dynamics and chemistry to explain the phenomenon.

• Demonstrated strong correlations between potential vorticity and temperature, O_3, HNO_3, and H_2O fields, illustrating the utility of potential vorticity for tracer studies. Observations give evidence of species transport associated with breaking planetary waves.

• Confirmed NO_2 diurnal change theory and provided latitude cross sections of the day/night ratio (Observations provided of diurnal change in lower mesospheric ozone). These results provide important data for in situ tests of photochemical theory.

• Provided detailed observations of constituents and temperature distributions during the major stratospheric warming event of the winter of 1979. This provides data for analyses of the warming period through calculation of derived dynamical quantities (e.g., winds, heat, momentum, and Eliassen-Palm fluxes) and by study of the global morphology and variability of constituent and temperature patterns.

• Discovered the presence and measured the variability of polar stratospheric clouds in both the northern and southern winter polar regions. These clouds, observed globally for the first time, have important implications for the water budget and heterogeneous chemistry.

• Measured optical depths of aerosols in polar regions that had been transported from much lower latitudes after an eruption of the El Chichon volcano on the Yucatan peninsula, providing information on horizontal transport times for use in model studies.

• Developed six-year climatology of polar stratospheric aerosols for use in climate impact studies. This is significant because of the suggestion that polar aerosols may have an important effect on climate.

• Detected SO_2 in the stratosphere directly (from the El Chichon eruption) for the first time. This gas is a precursor to sulfuric acid formation which is the main component of the stratospheric sulfate layer.

• Confirmed the effect of solar particles on stratospheric ozone during a solar proton event and found strong correlations of ozone variations at the 3 mb level with 27-day solar flux changes.

Solar Mesosphere Explorer

The Solar Mesosphere Explorer (SME) satellite was launched in October 1981. Its purpose was to investigate some of the factors influencing the ozone balance of the mesosphere and upper stratosphere, thus adding to our knowledge of the behavior of this very important atmospheric constituent. Some of the most significant discoveries noted to date include the following.

• Systematic observation revealed the ozone distribution at about 50-70 km by two techniques and 50-95 km by one technique.

• Observations of water vapor in the upper stratosphere are now also being obtained and their relationship to ozone is under study.

• It was discovered that day-to-day ozone variations at mesospheric heights are principally driven by temperature variations.

• It is indicated that solar flux variability significantly influences ozone distributions near the stratopause over the time scale of a solar rotation.

• Observation was made of the distribution and variability of stratospheric NO_2, a species which catalytically destroys ozone in the stratosphere. The sharp decreases in wintertime NO_2 at high latitudes (the "NO_2 cliff") were confirmed.

• Detailed observations of the response of mesospheric ozone to solar proton events showed very good agreement with photochemical theory, confirming that the catalytic destruction of ozone by hydrogen radicals (OH, HO_2) proceeds as expected.

• Large seasonal variations have been detected in ozone near the 80 km level. Present study suggests that these changes are due to the influence of breaking small-scale gravity waves.

Pioneer Venus

Pioneer Venus (launched in May 1978) was a two-spacecraft mission, with 4 entry probes, designed to conduct a comprehensive study of Venus' atmosphere. The most significant results include the following.

• Lack of an intrinsic planetary magnetic field was established.

• Shape of the bow shock and the volume of the solar wind interaction with the planet were clarified.

• Intense magnetic flux ropes were observed deep in the ionosphere.

• Ionospheric composition and temperatures were established.

• Nighttime auroral precipitation and emissions were observed.

• The extent of the nighttime ionosphere was established showing that it is maintained by a combination of transport from the day side and electron precipitation.

• An extended gas envelope, consisting of hot oxygen and hydrogen atoms, was observed, confirming the loss of hydrogen and oxygen from Venus by solar wind scavenging.

• Extremely low (about 100 K) nighttime thermospheric temperatures were observed.

• Lightning was detected by wave observations.

• At least four distinct cloud layers were found.

• Haze layers contain small aerosol particles, possibly droplets of sulfuric acid.

• Atmosphere circulation is dominated by large planetary-scale systems.

• A collar of polar clouds discovered, which may be part of a large atmospheric polar vortex.

Theory Program

The following are representative of a host of recent achievements in the areas of theory and computer simulations.

• Quasi-perpendicular bow shocks have been simulated at a new level of sophistication and have produced results in remarkable agreement with high resolution ISEE observations.

• Acceleration by self-generated, convecting, hydromagnetic waves has explained many properties of energetic diffuse ion populations observed upstream of both Earth's bow shock and traveling interplanetary shocks.

• First generation, two- and three-dimensional, global MHD models of Earth's magnetosphere have been obtained computationally; features such as the bow shock, magnetopause, cusp, tail lobes, and neutral points are all evident.

• Two- and three-dimensional simulations of magnetotail reconnection have shown many of the features predicted by fluid dynamics and seen in magnetospheric plasma observations.

• Analysis and simulations illustrated many important processes operating in the auroral zones and responsible for key observational features. Lower hybrid and ion cyclotron waves effectively heat and accelerate heavy ions; double layers and resistivity caused by spiky turbulence drive the electric fields necessary to produce auroral beams; and the electron cyclotron maser instability causes the terrestrial kilometric radiation.

• Major advances in our understanding of both fluid and MHD turbulence have been achieved. In the ionosphere, key features of the natural and artificial spread F have been reproduced in simulations. In the solar wind, magnetic data have been used to construct the three rugged MHD invariants and led to the suggestion that the solar wind is a strongly turbulent medium.

• Major progress in the theoretical understanding of beam plasma interactions resulted in the resolution of several outstanding issues. In the interplanetary medium it led to the most sophisticated modeling of type III bursts; in the ionosphere to the understanding of the extremely short energy deposition lengths associated with artificial beam injection.

• Compressible convection studies of the solar convection zone have shown that energy transport occurs on the space scale of giant cells and have demonstrated the existence of convective overshoot.

• Global thermospheric and ionospheric models have been developed and show that magnetospheric influences have an unexpectedly great importance, e.g., by inducing convection.

7 DETAILED MISSION PLANS—SOLAR AND HELIOSPHERIC PHYSICS

Introduction

The strategy for advancing solar and heliospheric physics combines in-situ measurements of the heliosphere with remote observations of the Sun from low-Earth orbit (LEO). Below we first describe the several pieces of the program and then, in Section C, discuss their relative priorities.

Program Descriptions

Free-Flyers for Solar and Heliospheric Physics

WIND

The WIND spacecraft is one of a network of spacecraft proposed as part of the International Solar Terrestrial Physics Program (ISTP). The overall goal of the ISTP is to develop a comprehensive and global understanding of the physical mechanisms by which energy generated at the Sun flows through the interplanetary medium and finally enters the Earth's magnetosphere and upper atmosphere. Understanding the coupling between solar and interplanetary processes and the Earth's magnetosphere, ionosphere, and atmosphere requires detailed knowledge of the source function. This can be obtained only through in situ measurements in the solar wind.

The WIND spacecraft has a central role in ISTP, for without detailed knowledge of the behavior of the solar wind upstream of its interaction with the Earth's magnetosphere, no comprehensive understanding of the effects of this interaction is possible. WIND will measure the properties of the heliosphere at 1 astronomical unit (AU) in the ecliptic plane while the International Solar Polar Mission (ISPM) acquires similar data far from the ecliptic. Study of magnetohydrodynamic turbulence, important for understanding both the formation and evolution of the solar wind and the behavior of laboratory plasma devices, requires the nearly continuous data coverage and the extensive data bases to be provided by the WIND instruments.

Further discussion of WIND will be found in the section on ISTP in Chapter 8.

SOHO

SOHO is a mission aimed at three distinct, yet interrelated plasma regimes, the solar interior, the corona, and the solar wind. Experiments on SOHO will use the methods of solar seismology, spectroscopic plasma diagnostics, and in-situ measurements to derive the physical state, chemical composition, and the internal and bulk motions of the plasma structures that make up the Sun and heliosphere. The objects of the study will range from the dense matter hidden inside the Sun, in the thermonuclear furnace and in the radiation and convection zones; through the tenuous corona, where matter is held together and possibly heated and accelerated by magnetic fields; far out into the interplanetary medium, where the solar mass loss manifests itself as the solar wind. The detailed data acquired by SOHO, combined with sophisticated, well-developed methods of interpretation, will allow tests of the numerous models of plasma structures. Examples of such structures are the solar convection zone, coronal magnetic loops, and the sharp boundary layers between low and high speed solar wind streams.

The primary objectives of SOHO are as follows.

- Use solar oscillations to probe the solar interior structure from the core to the solar "surface", or photosphere.
- Determine the angular rotation profile of the solar interior and measure the solar gravitational quadrupole moment.
- Measure variations in solar irradiance from minutes and days to weeks and years to ascertain effects of solar activity on solar luminosity.
- Study the generation of the solar wind through measurements of plasma velocities, temperatures and densities out to 5 solar radii.
- Locate sources of low speed solar wind.

• Determine how coronal transients propagate through the corona and how and where they are accelerated.

• Obtain high resolution temperature, density, velocity, and magnetic measurements in an effort to determine the origin of coronal heating.

SOHO is a three-axis stabilized spacecraft that is to be placed in a halo orbit around the L_1 Lagrangian point at 1.5×10^6 km from Earth. The spacecraft is to be built by the ESA with experiments provided by both European and U.S. scientists.

Solar Probe

The general problem of the origin of the solar wind has been a focus of observational and theoretical activity since the original theoretical work of E.N. Parker. Direct measurements of the solar wind plasma, the interplanetary magnetic field, the energetic particle population, and associated wave-particle interactions are available, but only at distances greater than the 0.3 AU perihelion distances of Helios 1 and 2. From the solar surface out to a distance of about 60 solar radii, we must rely on indirect observations and theoretical extrapolations. We recommend a Solar Probe mission whose primary objective is to carry out the first in situ observations of the solar wind plasma and fields (electric and magnetic) near the source of the wind in the solar atmosphere. Included will be a detailed study of energetic particles which will yield important diagnostic data on particle acceleration processes and coronal structure.

The spacecraft must be placed in an orbit that will bring it as close to the Sun as possible and still survive to provide useful data near closest approach. We anticipate a perihelion distance of 4 solar radii, where we expect the local wind speed to be about 50 km/s, the electron and ion plasma temperatures to be about 10^6 K, and the plasma density and magnetic field strength to be less than 10^6 electrons/cm^3 and 10^5 gamma, respectively.

Theories of solar wind origin place the transition region from subsonic plasma flow to supersonic flow somewhere between 1 and 10 solar radii. Radio scattering experiments on Viking during superior conjunction suggest a critical point closer to 10 solar radii. In situ measurements should clarify this issue.

The location of the critical point and the plasma properties (speed and temperature) of the supersonic wind will depend greatly on the physical processes that heat the corona. Theoretical studies suggest that the proton temperature profile is very sensitive to these heating processes. It is not clear whether the corona contains an extended region of heating (out to as far as 20 solar radii) or undergoes adiabatic expansion beyond the solar surface. Plasma temperature data and observations of the wave types and amplitudes should lead to the identification of the important heating and acceleration mechanisms.

Many other important problems can be studied with Solar Probe, including a detailed characterization of coronal streamers, the place of origin and the boundaries of high speed and low speed flows close to the Sun, the extent of heavy element fractionation and elemental abundance variations, and the scale sizes of inhomogeneities and the development of the magnetohydrodynamic turbulence that characterizes the solar wind near 1 AU and beyond. The Solar Probe mission can also study the solar spin down rate through measurements of solar wind angular momentum flux.

Further study needs to be carried out to determine the best method of designing detectors that are required to look in the direction of the Sun.

In previous studies on the concept of a solar probe (*Starprobe: Scientific Rationale*, J.W. Underwood and J.E. Randolph, JPL Publ. 82-49, 1982), several other investigations were also included in the potential payload, e.g., imaging, a drag-free experiment for studying relativistic effects, and measurement of the solar gravitational quadrupole moment*. While these investigations undoubtedly have important scientific objectives, the *primary objective* of the mission is the study of the solar wind acceleration region. In order to fit this mission into our implementation plan (Figure 4), cost considerations have forced us to define the mission to address the prime objective *only*.

* Much progress can be made in measuring the solar gravitational quadrupole moment from solar oscillation studies.

With additional funds, these other worthwhile objectives could also be addressed.

Solar Polar Orbiter

The heliosphere is known to have a complicated three-dimensional structure. The magnetic field is a tight spiral near the solar equatorial plane, but is expected to be essentially radial over the solar poles. Coronal holes, one of the sources of high speed solar wind, are expected to produce quasi-steady high speed flows over the solar poles during much of the solar cycle, whereas at low latitudes interacting high and low speed flows predominate.

To understand heliospheric conditions at low solar latitudes has required numerous missions, e.g., Explorers, Pioneers, Mariners, and Voyagers. To understand heliospheric conditions at high latitudes will similarly require repeated missions. In 1986, NASA and ESA will fly the first exploratory mission over the solar poles, the ISPM. However, as with most exploratory missions, ISPM will probably uncover more questions than it will answer, and follow-on missions will be required.

The objective of the Solar Polar Orbiter (SPO) would be to provide a detailed, repeated study of conditions at all heliographic latitudes. In circular orbit, SPO will observe the heliosphere at constant radius and thus will distinguish latitude from radial effects. With a circular orbit at less than or equal to 1 AU, and thus an orbital period less than or equal to 1 year, SPO should be able to make several passes over the solar poles in a nominal mission lifetime, and thus distinguish spatial from temporal effects.

No detailed study of an SPO mission has been done in recent years. However, the required orbit should be achievable through the use of a low-thrust, continuous acceleration propulsion system such as solar-electric propulsion. For example, it may be possible to launch SPO in the direction of the Earth's orbit, and use solar electric propulsion to tilt the orbital plane in heliographic latitude.

The SPO spacecraft should carry a full complement of plasma, energetic particle, magnetic field, and radio wave instruments, similar to what is to be flown on ISPM. In addition, SPO should have pointing capability, through the use of a despun platform on a spinning spacecraft, or as a three-axis stabilized spacecraft, for detailed solar observations using a coronagraph, x-ray telescope, and similar photon observing instruments.

Mission design for SPO should be undertaken in the mid-1990s, following a thorough analysis of the results from ISPM. Launch should occur in the late 1990s.

The principal technical development required for SPO is solar-electric propulsion system, or its equivalent, for low-thrust, continuous acceleration. In the cost projections for SPO it is assumed that such development will not be charged against the mission costs, because the need is common to several proposed programs. Also, studies need to be conducted on the impact of a continuous propulsion system on particle, field, and photon instrumentation, and on the measurements these instruments make.

Solar-Heliospheric Research with the Shuttle

Remote observations of the sun and corona will be made with Shuttle-borne instruments ranging in size from small Spartan experiments to moderate Spacelab/Sunlab instruments to large facility-class instruments. After Shuttle experience is obtained, we envision that appropriate facilities and moderate instruments will evolve into a Space Station-based Advanced Solar Observatory (ASO) as the primary means for remote sensing in the next decade. Development of new instrumental techniques and exploration of some solar phenomena do not require large facilities. These problems can be addressed using smaller experiments of the PI class, suitable for Shuttle, free-flyers, sounding rockets, and balloons. Shuttle-based observations include measurements of

- energy and mass flux from the photosphere through the corona;
- magnetic and velocity fields and their evolution and interactions;
- temperature and density structure of the solar atmosphere;
- changes in solar radiative flux; and
- some coronal processes that may govern

the generation, structure and variability of the solar wind.

We have identified three Shuttle programs that are critical for solar-heliospheric physics.

1. Spartan. The Spartan program, which is a successor to the sounding rocket program, can fly innovative, relatively small and inexpensive instruments prepared on a rapid time scale. The Spartan carrier will contain a pointing system, power supply, and tape recorder. When placed into orbit by the Shuttle, the Spartan will be a free-flyer for one to two days before being recovered by the Shuttle. To continue adequately research currently done with sounding rockets, Spartan flights with solar-heliospheric experiments should be flown at least three times per year.

2. Spacelab/Sunlab. This program provides opportunities to fly moderate sized instruments in complementary groups mounted on the Instrument Pointing System (developed by the ESA). The experiments will be attached to a pallet fixed in the Shuttle bay. Interactive control of the experiments by payload specialists is an important part of this program. Flight opportunities should be roughly every two years to provide for orderly instrumental evolution from Spartan to more advanced programs.

3. Facility Class Instruments. To attain the highest spatial, spectral, or temporal resolution requires experiments that take full advantage of the Shuttle's electrical power, large payload capacity, and data handling capabilities. Instruments in the Facility Class include telescopes, spectrometers, filters, photometers, polarimeters, and imaging detectors covering most of the electromagnetic spectrum. Facility development begins with the Solar Optical Telescope (SOT), designed to measure physical phenomena from the photosphere through the transition region, followed by the Pinhole Occulter Facility (POF), designed to image high energy events in the corona and to measure dynamical phenomena of the corona. Three additional facilities have been identified: a soft x-ray facility, a high energy facility, and an extreme ultraviolet telescope (EUVT). These facilities should be developed as soon as possible to complement SOT and POF.

The Solar Optical Telescope

The purpose of SOT is to study physical processes on the Sun with an instrumental angular resolution of 0.1 arcsec. This corresponds to 70 km and is about half an atmospheric density scale height. We know that much of the fine structure and energy transport in the solar atmosphere are closely associated with the strong magnetic field concentrations associated with sunspots and smaller flux tubes in the chromosphere and corona.

SOT will study (by remote sensing) the solar atmosphere from the photosphere, where the gas pressure plays a major role in containing the magnetic fields, to the upper chromosphere and lower transition region, where magnetic forces are dominant. This requires spectral coverage extending from the near infrared to the far ultraviolet.

Two specific scientific problems can be described that illustrate some of the capabilities of this facility.

1. In the solar atmosphere, the magnetic fields and fluid motions interact in such a way that at the solar surface the fields are highly inhomogeneous. A large fraction of the magnetic flux is clumped into very intense flux tubes. Field strengths of 1500 gauss contained within flux tubes of a few hundred kilometers in diameter are common even outside of sunspots. SOT will help answer questions of how this clumping arises and how the magnetic flux ultimately disappears after reaching the surface. Both processes may be an essential part of the dynamo mechanism of solar magnetic field generation that is believed to be responsible for the solar magnetic field and cycle.

2. It has become increasingly clear that the solar magnetic fields play a key role in the heating of both the chromosphere and the corona. Skylab data showed that coronal forms are tied to magnetic field geometry while OSO-8 data showed that acoustic shock waves are not sufficiently strong to carry the necessary energy into the corona. SOT is expected to provide quantitative measures of the coupling between photospheric magnetic field stresses and chromospheric and coronal heating.

The Pinhole Occulter Facility

The Pinhole Occulter Facility (POF) is designed to image hard x-ray sources with unprecedented angular resolution. The goal is to study the production of solar energetic electrons, which constitute the bulk of the initial energy release in solar flares. Studies by POF of the sites and phase relationships of particle acceleration relative to the magnetic field and fluid dynamics will provide insight into the physical mechanisms operating. POF will provide more than an order of magnitude improvement in spatial resolution.

A second major area of study is the massive acceleration of large volumes of coronal plasma in the form of coronal transients. These mass ejections have been studied in the outer corona at low resolution by Skylab, SMM, and the P-78 satellites. Because of its 50-m length and larger telescopes, POF will be able to improve significantly the angular resolution of previous studies, to obtain clean observations of both the middle and outer corona and to perform detailed spectroscopy of the coronal plasma. Two specific objectives of POF using these instruments are described below in more detail.

1. *Coronagraphs.* These instruments will provide new data on some of the processes by which energy and momentum are deposited in both the expanding open field regions and in the more slowly evolving closed magnetic field regions of the corona. It is not currently known whether the heat input to the corona is evenly distributed or localized; nor is it known whether the heating occurs continuously or sporadically. The spectral diagnostics of the coronal plasma together with observations of its dynamical properties at high spatial resolution are expected to provide answers to these questions.

2. *Solar X Rays.* Imaging hard solar x rays will aid in understanding the mechanisms by which electrons are accelerated to high energies during the impulsive phases of solar flares. It is currently thought that hard x rays are produced by the impact of these electrons on the denser regions of the lower atmosphere. Observations using POF, coupled with the high resolution studies using SOT, will provide essential knowledge of the spatial and temporal relationships between the energy releases in electromagnetic radiation over the range of a few eV to over 100 keV.

The Soft X-Ray Telescope

The primary purpose of the Soft X-Ray Telescope (SXRT) is to study the thermodynamic and hydrodynamic structure of the corona in relation to its magnetic field patterns. High to moderate resolution spectrographs provide plasma diagnostics in the temperature range from approximately 10^6K to 10^8K. This soft x-ray spectral data, arising mainly from the thermal plasma, is complementary to the hard x-ray data from the POF, arising mainly from non-thermal electron streams.

Past experience has shown that the soft x-ray region from approxmately 300 Å to 1.75 Å (40 eV to 7.1 keV) is the richest spectral region for studies of the corona. The absence of strong background radiation from the photosphere and chromosphere in this spectral region allows the corona to be observed against the disk of the Sun. This has the triple advantage over limb observations of greatly simplifying the effects of line-of-sight integration, of showing the lateral structure of the corona in two dimensions, and of showing the locations of coronal structures relative to magnetic field patterns in the photosphere.

Soft x-ray data obtained with Skylab and other space experiments have radically altered our concepts of the corona, particularly with respect to the importance of magnetic fields in both heating and shaping the coronal structure. However, it is clear from these same observations that the true coronal structure is unresolved at 2 arcsec, which is the best resolution yet attained for a sustained period of time.

The SXRT has a design goal of 0.5-arcsec spatial resolution. The collecting area of 1140 cm^2 is approximately twice the collecting area of the High Energy Astronomical Observatory(HEAO)-2 telescope and 27 times that of the experiment on Skylab. As such it will offer major advances in both spatial resolution and sensitivity.

Two examples selected to illustrate the

objectives of the SXRT are (1) study of the heating of coronal plasma and (2) investigation of the thermal properties of flares and the conversion of stored magnetic energy into thermal energy during the flare main phase. Coronal heating is known to fluctuate spatially on scales down to 1 arcsec or less and temporally on scales of minutes. The spatial resolution of 0.5 arcsec provided by the SXRT should be sufficient to isolate regions in which the heating fluctuations and fluid motions are relatively coherent. By combining the SXRT with the SOT, the fluctuations in coronal heating and fluid motion can be correlated with related fluctuations in the chromosphere and with photospheric magnetic field fluctuations.

Major flares typically heat the thermal plasma in the corona to temperatures in excess of 10^7 K over volumes that are large compared to those in which the non-thermal electrons are concentrated. Just how the thermal flare plasma relates to the preceding impulsive non-thermal flare events is unclear. The SXRT, in combination with the POF and the SOT, will provide the type of data needed to answer such questions.

The EUV Telescope

The primary purpose of the EUV Telescope (EUVT) is to study the upper chromosphere and the chromosphere-corona transition region with high spatial resolution ($\lesssim$ 0.5 arcsec). Within these regions the temperature rises from below 10^4 K to over 10^6 K in a short distance. The principal radiation from these regions lies in the EUV and XUV at wavelengths below 1600 Å. The exceedingly high temperature gradients lead to a major flow of energy from the corona back down to the chromosphere by thermal conduction. Additionally, there are strong vertical fluid currents with average mass fluxes exceeding those in the solar wind by about two orders of magnitude. The upper chromosphere and transition region are the least understood regions of the solar atmosphere. The temperature gradients are so steep that electrons in the high energy tail of the thermal velocity distribution penetrate into regions of much different temperature giving rise to non-Maxwellian distributions and a breakdown of classical thermal conduction. Moreover, the vertical fluid currents are important components of the energy transport.

Two objectives for the EUVT are (1) to understand the mechanisms giving rise to the fluid motions in the transition region and upper chromosphere and (2) to understand the multifaceted energy transport within and through these layers. How are the upflows and downflows related? Are the driving forces hydrodynamic or are magnetic forces essential? How does the solar wind emerge from these more massive flows? These questions are typical of those that can be addressed by the EUVT, particularly when used in concert with the SOT, the XUVT, and the SXRT.

High Energy Facility

The primary purpose of the High Energy Facility is to study acceleration of ions. Observations acquired during the last solar maximum demonstrated that gamma-ray measurements open up a new window for studying particle acceleration on the Sun, the most powerful natural particle accelerator in the solar system. Gamma-ray lines from many different elements (C, H, O, Fe, Mg, Sc, N and Ne) have been detected in solar plasmas. SMM observations indicate that ion acceleration to about 10 MeV is a common phenomena in solar flares. In addition, energetic neutrons (50-500 MeV) have been detected. Because of these results, there is strong interest in new observations with instrumentation of high sensitivity, as could be provided by a high energy facility. The High Energy Facility, together with other solar facilities such as POF and SOT, provides a powerful tool for addressing the fundamental processes of particle acceleration.

Explorers for Solar and Heliospheric Physics Studies

The active utilization of the Explorer Program would be a great benefit to solar and heliospheric physics. Rather than endorse any particular mission, however, we recommend that the selection be the result of a competitive process that encourages innovation, in accord with the recent recommendation of this committee contained in *A Strat-*

egy for the Explorer Program for Solar and Space Physics, NAP 1984. We briefly present two examples of such missions that are discussed in greater detail in that report.

Advanced Solar-Wind Composition Explorers

A complete chemical and isotopic analysis of the solar wind would provide information on some, and probably all of the following topics: improved knowledge of solar-wind mass/charge fractionations which, in turn, would shed light on the solar-wind acceleration process and refined solar system abundances; tests of the fundamental assumption that the Sun and planets formed from a common reservoir; limits on integrated solar surface nuclear processes; and constraints on solar structure and evolution. Instrumentation to be flown on ISPM and WIND will allow determination of the elemental and ionic-charge compositions of all major solar-wind ions from H through Fe. Advanced instrumentation is required for studies of the rarer elements and isotopic abundances. Two different, complementary approaches appear to be possible within the budgetary constraints of the Explorer program. In one approach an advanced energetic ion mass spectrometer would be placed on a spacecraft that spends a significant amount of time beyond the Earth's bow shock. Direct samples of coronal material can also be provided by energetic solar particle measurements spanning the energy range from about 10 keV/nucleon to 100 MeV/nucleon which would significantly enhance the interpretation of the solar wind measurements by providing data for many additional elemental and isotopic species. Because this set of instrumentation would probably be quite massive, there might be few, if any, other instruments on board. Alternatively, it is possible to perform a solar-wind sample return mission in which high-purity collector material is exposed to the solar wind for about 2 years, and is then retrieved for performance of chemical and isotopic analyses in terrestrial laboratories.

Coronal Radio Probe Explorer

The objectives of this mission would be to obtain new data on the coronal plasma below the solar altitude accessible to the Solar Probe. This lower region of acceleration of the solar wind can be probed with radio techniques (time delay, spectral line broadening, scintillation, and Faraday rotation) by placing a spacecraft carrying a radio beacon (at several frequencies) on the far side of the Sun from the Earth. Orbits could be picked so the ray path would either slowly circle around the solar disk or move along a solar radius vector.

Long-Term Solar and Heliospheric Measurements

Solar and heliospheric phenomena vary over a great range of time scales. Well-established, cyclic phenomena occur at the 11-year and 22-year sunspot and magnetic cycle periods. Careful study of the long-term time dependences of selected solar and heliospheric parameters will provide valuable insight into fundamental solar and heliospheric processes that is not available in any other way.

Solar Constant

Variations in the solar radiative output not only have impact on the Earth's ionosphere and atmosphere, but also provide fundamental knowledge about the Sun and its internal structure and dynamics. For our understanding of deviations of the Sun from its equilibrium steady state to progress, long-term satellite monitoring of the total solar energy output and its distribution over wavelength should take place. Unfortunately, there is no one agency dedicated to the support of long-term monitoring of this type, and no one agency has devoted sufficient resources or interest in this area to do it properly. Long-term, synoptic observations are often the only means of discovering linkages in the behavior of elements of the system, despite the absence of clear cause-and-effect relationships.

Long-Term Monitoring of Interplanetary Particles and Fields

The study and elucidation of solar and terrestrial interactions that are mediated by the solar wind or by solar energetic particles requires a commitment to long-term and continuous monitoring of the interplanetary plasma, magnetic field, and cosmic rays. For example, further study of suspected 22-year effects in the intensity of cosmic rays may lead to better understanding of the solar magnetic cycle and the turbulent dynamo that is the source of the solar magnetic field. Studies of magnetohydrodynamic turbulence are seriously hampered by discontinuous data records caused by incomplete satellite tracking.

Theory and Modeling

Magnetic field reconnection should form one important aspect of theoretical studies supported by ISTP, as should the study of large-scale plasma flows within the magnetosphere and ionosphere. In the *Plasma Turbulence Explorer Study* report, the need for a multi-spacecraft analysis of interplanetary fields and fluid velocity data coupled with theoretical studies was proposed as one means of progressing in understanding of magnetohydrodynamic turbulence. Such a study, which might include three-dimensional modeling of MHD turbulence using Cray-class computers, might lend itself to a "non-hardware" mission because the manpower and computer resources required exceed the nominal magnitude of awards under the STTP. Preliminary work in this area has been supported by R&A funding, guest investigator grants under the ISEE program, and other institutional support provided by NASA.

Mission Operations and Data Analysis

An example of an extended mission requiring MO&DA support may be provided by ISPM. The prime mission phase allows for a pole-to-pole passage during solar maximum conditions. If as expected, ISPM survives beyond the second polar pass, an extended mission could provide invaluable data on solar and heliospheric conditions at high solar latitudes during other portions of the solar cycle.

A second example is the complement of deep-space planetary missions, Pioneer 10 and 11 and Voyager 1 and 2. These contribute unique information about the heliosphere and, at present, provide the only possible means of detecting the boundary between the solar system and the interstellar medium.

Finally, IMP-8 is, at present, the only means of studying the solar wind and its effects on the terrestrial environment.

Research and Analysis

The early stages of instrument development (preflight through testing with sounding rockets) are supported by the R&A program. Several such developments are crucial to the success of the flight programs described in the paragraphs above. Examples are a multilayer mirror for imaging solar x rays, a space qualified instrument for mapping solar oscillations with the SOHO spacecraft, and advanced solar-wind and energetic-particle composition analyzers.

Another component of the solar and heliospheric R&A program is obtaining and analyzing correlative data from many types of ground-based observatories. The value of solar observations from SMM, the SOHO spacecraft of ISTP, the Shuttle, and the space station/platform can be greatly enhanced by simultaneous observations of additional facets of the phenomena under study. Examples include coronagraphic and magnetographic observations from ground-based solar observatories, maps of solar radio emission obtained with the Very Large Array and other facilities, and the observation of scintillation of radio sources caused by coronal and interplanetary disturbances.

Finally, there are several types of laboratory and suborbital research that complement and enhance the rest of NASA's solar and heliospheric physics program and should therefore be supported by NASA as well as by other agencies (e.g., NSF, DOD). This research includes laboratory simulations of solar plasma processes, such as magnetic reconnection in solar flares, and the measurement of cross sections required to interpret solar data. Long duration balloon flights may prove to be a very cost effective and valuable technique for obtaining data on hard x rays and gamma rays emitted during solar flares.

The four principal components of the R&A program—theory and analysis, instrument development, correlative observations, and complementary research—are listed here in approximate priority order. The scientific return from the R&A program is high, and we recommend an increase in its level of funding starting in 1990, after the peak spending years for UARS and ISTP.

Technology Development

The new technology requirements of the solar and heliospheric physics program can be conveniently divided into components, instruments, and spacecraft capabilities.

Many different instrument and facility development requirements have been discussed in the paragraphs above. Except for the components listed immediately above, development of these instruments/facilities requires the normal sequence of detailed design and hardware development, but little or no new technology. Thus, although the developments require significant funding for the design and test of space-qualified hardware, the risks of significant schedule slips or cost growth are not high.

All the approved solar and heliospheric physics missions, ISTP, and the solar instruments/facilities planned for the Shuttle or space station/platform can be implemented with existing spacecraft technology; i.e., no enabling technology development is required for those missions. New technology is needed for the Solar Probe and SPO, however. The concept of obtaining data with a spacecraft located 3 solar radii from the solar surface is predicated on the development of a heat shield that keeps the instruments and spacecraft within operating temperature range, without ablation of enough material to prevent the observation of the ambient coronal plasma. NASA has already started the development of such a heat shield and we recommend that this development be continued at a pace consistent with a new start for the Solar Probe in 1991.

Advanced propulsion is required for the SPO. Our proposed time line of mission sequences is based on the assumption that such a capability, probably based on solar powered ion thrusters, will be available by 1997. If it were available, a low-thrust propulsion system could also be used to enhance the scientific return of the Solar Probe Mission by decreasing the period of the eccentric solar orbit to allow more than one close solar passage within the useful lifetime of the spacecraft. Advanced propulsion is also under consideration by the planetary community for a multiple asteroid rendezvous mission. Thus, we recommend that NASA either accelerate its development of this technology or join forces with some other agency working on advanced propulsion.

Priorities

We assume that the following missions are approved and will be flown: International Solar Polar Mission, solar instruments on Spacelab 2 and Spartan 2, and the Solar Optical Telescope Facility. For new missions for solar-heliospheric physics, we have identified the first and second priorities.

- WIND and SOHO components of ISTP
- Pinhole Occulter Facility

In addition, we have prioritized other programs in the following categories:

- Major Free-Flying Missions
  - Solar Probe
  - Solar Polar Orbiter
- Explorer Missions
  - Solar-heliospheric Explorer missions at the rate of one per two or three years
- Shuttle Missions
  - Additional moderate-sized solar instruments beyond the Spacelab-2 experiments
  - Spartan missions to succeed the sounding rocket program
  - Additional flights of the SOT with co-observing instruments and enhanced focal plane instruments
  - Additional solar facilities: Soft X-ray Telescope, High Energy Facility, and EUV Telescope Facility
- Space Station Missions
  - Deployment of Solar Optical Telescope and other facility class and appropriate instruments as the start of the Advanced Solar Observatory

There are several important activities that are not specifically mission related. These include the Theory and Modeling Program and Research and Analysis. Both of these

SOLAR AND HELIOSPHERIC PHYSICS PROGRAM

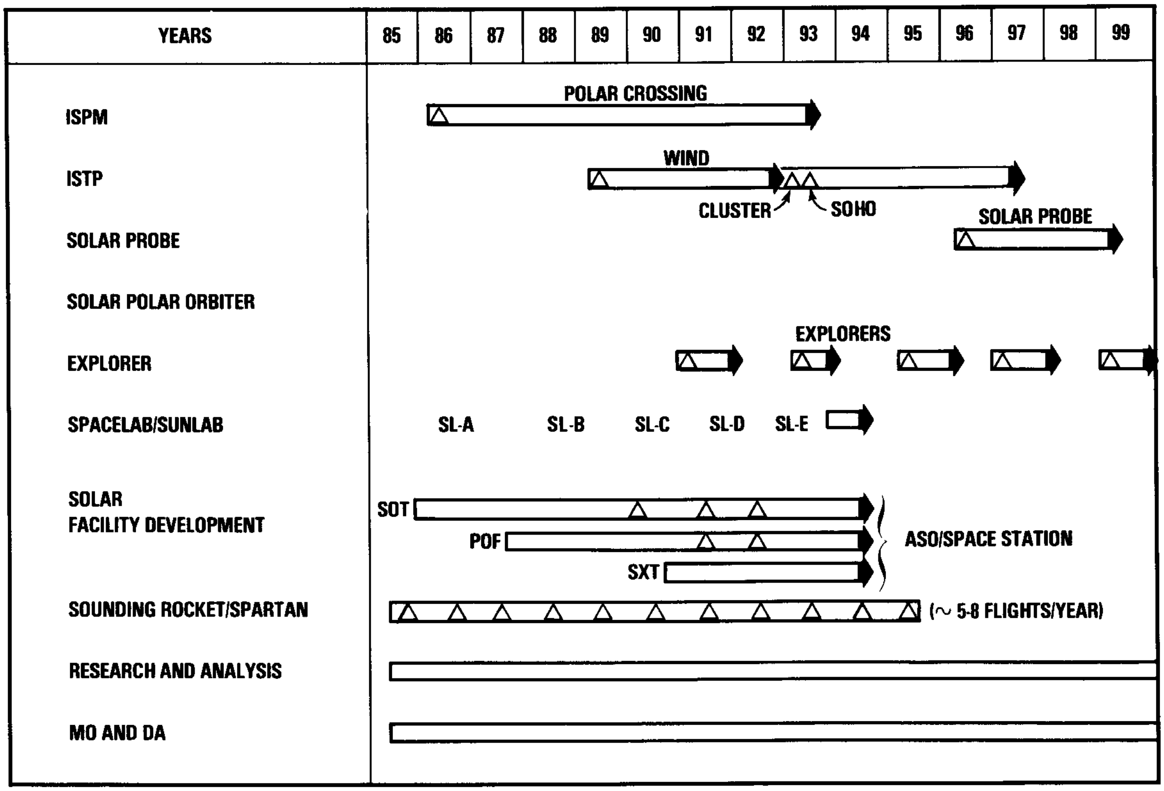


FIGURE 5

activities are prerequisites for a healthy program in solar-heliospheric physics. *Within the Research and Analysis program we assign priorities in the following order: (1) theory and analysis, (2) instrument development, (3) correlative observations, and (4) complementary research.*

The time line shown in Figure 5 for the solar and heliospheric physics program resulted from considerations of scientific priorities, funding constraints, technological readiness, and the phase of the solar activity cycle.

The program of solar-heliospheric physics discussed here is constrained by funding. As a result we excluded a number of exciting missions that might be reconsidered in the twenty-first century. For example, a heliostationary orbiter, whose period equals the rotation period of the Sun, would permit continuous observations of the evolution and decay of solar activity and unique in situ measurements of the evolution of the heliosphere at one solar longitude. Another example is a Heliosphere Boundary Probe intended to locate and explore the heliopause and to explore the particle, field, and plasma environment of interstellar space.

Funding constraints also caused us to reduce the capabilities of several proposed missions. For example, an early study of the Solar Probe (*Starprobe: Scientific Rationale*, J.H. Underwood and J.E. Randolph, JPL Publ. 82-49, 1982) with an experiment payload that included imaging, drag-free experiments, and a maser clock was estimated to cost approximately $1 billion. The mission recommended here, however, addresses only our highest priority objective, i.e., the investigation of the sources of the solar wind. More comprehensive missions should be considered for implementation early in the twenty-first century.

8 DETAILED MISSION PLANS—PLASMA PHYSICS

Introduction

The critical scientific objectives of space plasma physics are to

- trace the transport of energy, momentum, and matter from the Sun, through the interplanetary medium, across the magnetospheric boundaries, through the magnetospheres and ionospheres into and out of the upper atmospheres;
- understand the physical processes that control the entry, transport, storage and release of plasma and of energy and momentum in magnetospheric systems, with special emphasis on understanding basic physical processes not readily accessible to laboratory investigation;
- investigate the processes that couple distinct parts of the system including the solar wind, magnetospheres, ionospheres, and upper atmospheres; and
- describe and understand fully the sources and sinks of magnetospheric plasmas.

These objectives are implicitly included in the report, *Solar-System Space Physics in the 1980's: A Research Strategy* prepared by the Committee on Solar and Space Physics in 1980. Mission planning must recognize the requirement to perform measurements directed toward these objectives. Integration of theoretical activities in support of mission design and development and in analysis of measurements will accelerate progress in understanding the complex magnetospheric system.

Program Descriptions

In this section a mix of major, moderate, and small programs with associated MO&DA and R&A resource requirements is discussed. The near-term program through the early 1990s and a longer-term program that utilizes the Shuttle/Space Station/Platform systems beyond 1992 are described.

Major Programs

International Solar-Terrestrial Physics Program

The International Solar-Terrestrial Physics Program (ISTP) is being planned by NASA, ISAS, and ESA in order to develop a comprehensive global understanding of the production and flow of energy within the Sun, the heliosphere, and Earth's magnetosphere and ionosphere. As of the summer of 1984, the ISTP program is planned to begin development in 1986 and will continue operations through the 1990s. The program will define the complex relationships that exist within the solar-terrestrial system. Here we describe each of the six spacecraft components of ISTP.

WIND. WIND is proposed to be built and launched by NASA (1989) as the first of this series. It will utilize lunar swing-bys to maintain its apogee on the day side of Earth and thus to survey the upstream region out to distances of 250 R_E during perhaps the first two years after launch. After that time, plans include the possibility of placing WIND into a halo orbit about the L_1 libration point. WIND will make correlative measurements with the rest of the network of spacecraft in the ISTP program (SOHO, POLAR, EQUATOR, GEOTAIL, and CLUSTER). WIND will

- investigate sources, acceleration mechanisms, and propagation processes of energetic and solar wind particles in correlation with SOHO;
- provide the complete solar wind plasma, energetic particle and magnetic field inputs for magnetospheric and ionospheric studies to support POLAR, EQUATOR, GEOTAIL, and CLUSTER;
- determine the magnetospheric output (particles, beams, and waves reflected from the bowshock and the magnetopause) in the upstream region;
- investigate basic plasma processes occurring in the solar wind near Earth; and

• provide baseline observations in the ecliptic plane to be used in correlation with observations made at high heliospheric latitudes by the ISPM spacecraft.

POLAR. POLAR is one of the three magnetospheric components of ISTP. It would be built and launched by NASA (1991) into an eccentric polar orbit having perigee at approximately 2 R_E and apogee at about 8.5 R_E. It will make correlative measurements of plasma, energetic particles, and electric and magnetic fields in conjunction with WIND, EQUATOR, GEOTAIL, and CLUSTER. POLAR will have the following magnetospheric and ionospheric plasma physics objectives:

• determine the role of the ionosphere in substorm development and in the overall magnetospheric energy balance, correlating data with those from EQUATOR and GEOTAIL;

• measure plasma energy input through the dayside cusp region, correlating data with those from WIND and SOHO;

• determine characteristics of ionospheric plasma outflow and energized plasma inflow to the atmosphere, in support of the UARS mission;

• study the characteristics of the regions wherein auroral plasma is accelerated, correlating data with those from CLUSTER;

• provide global, multispectral auroral images of the footprint of magnetospheric energy deposition into the ionosphere and upper atmosphere at high latitudes; and

• measure magnetic field signatures of field-aligned currents.

EQUATOR. EQUATOR is another of the three magnetospheric components of the ISTP Program. It would also be built and launched by NASA (1991) into an equatorial orbit with perigee at about 2 R_E and apogee near 12.4 R_E. It will make correlative measurements of plasmas, energetic particle populations, and of electric and magnetic fields in conjunction with POLAR, GEOTAIL, and CLUSTER. EQUATOR will have the following magnetospheric objectives:

• determine overall magnetospheric energy balance and the effects of substorms in populating the ring current and inner magnetosphere, correlating data with those from POLAR and GEOTAIL;

• help determine the role of internal magnetospheric substorm trigger mechanisms and separation of such effects from external trigger mechanisms through correlations with SOHO and WIND;

• provide direct observations of the interactions between geomagnetic tail and ionospheric plasmas in the equatorial magnetosphere;

• measure the transport, energization, and storage of ionospheric and tail plasmas in the near-Earth plasma sheet and ring current, correlating data with those from GEOTAIL and POLAR; and

• measure the coupling between the solar wind and the magnetosphere at the subsolar magnetopause, correlating data with those from WIND and SOHO.

GEOTAIL. GEOTAIL is the third magnetospheric component of ISTP. It would be built by Japan and launched by NASA (1991) into a lunar swing-by orbit in order to maintain an apogee in the distant (80-250 R_E) magnetotail for a period of about 1 year. After this time, a propulsion system will place GEOTAIL into an equatorial orbit of 8 R_E by 20 R_E for making detailed measurements of substorm processes in that region. GEOTAIL will have the following important magnetospheric objectives:

• determine the overall plasma and field properties in the distant geomagnetic tail region;

• determine the relative roles of the distant and near geomagnetic tail in substorm processes, and in the overall magnetospheric energy balance correlating data with those from EQUATOR, POLAR, and WIND;

• study the initiation of reconnection processes in the geomagnetic tail and observe the microscopic properties of the energy conversion mechanisms in this reconnection region, correlating data with those from EQUATOR, CLUSTER, and POLAR;

• separate the relative contributions of the ionosphere and solar wind to the geomagnetic tail plasma; and

• study the entry, energization and transport of plasma in interaction regions such as the inner edge of the plasma sheet, magnetopause and bow shock.

CLUSTER. CLUSTER consists of one main and three companion spacecraft, each having on-orbit propulsion capability to adjust inter-satellite separations from 100 km to up to several Earth radii. The CLUSTER would be an ESA program designed for launch either by an Ariane IV booster or by a Space Shuttle flight. Data from CLUSTER will be correlated with those from other ISTP spacecraft as part of the overall international program. The proposed mission plan is to place the CLUSTER spacecraft into a polar orbit 20 R_E x 3 R_E. CLUSTER will perform correlative multipoint measurements at known separations of its four individual spacecraft, and will

- explore the boundary regions of the magnetosphere as a readily accessible example of the sharp interface between two cosmical plasmas and thereby to investigate the detailed processes by which mass, momentum, and energy are transported across boundaries such as the magnetopause;
- study the magnetic reconnection processes and the small scale MHD structure and plasma acceleration associated with reconnection regions;
- study MHD turbulence, vortex formation, and eddy diffusion, especially in the polar cusp and boundary regions;
- investigate the structure and properties of collisionless shocks, including the bow shock, and the associated wave generation and particle acceleration;
- determine the small scale properties of the solar wind flow around the Earth; and
- utilize the four-spacecraft configuration to determine unambigously the three-dimensional shape and dynamics of magnetic structure with scale sizes from 0.1 R_E to 10 R_E (four-point measurements can determine the curl of a vector field, i.e., the spatial current density).

SOHO. The SOHO spacecraft is proposed to be three-axis stabilized to allow a variety of optical instruments to view the solar surface and corona from an L_1 libration point orbit. SOHO is proposed to be an ESA program, and will be designed to be launched by either an Ariane IV booster or from the Space Shuttle (1993). Although its primary objectives are to observe solar phenomena (see Chapter 7), it is planned to carry plasma instrumentation for in-situ measurements of the solar wind. SOHO will have the following objectives that are important to the magnetospheric plasma physics involved in the overall ISTP program:

- study the solar wind plasma, collisionless shocks in the solar wind and other irregularity structures, correlating data with those from WIND; and
- provide information on solar wind input functions for use in interpreting data from WIND, POLAR, EQUATOR, GEOTAIL, and CLUSTER.

Explorers for Magnetospheric Plasma Physics

While many of the important global aspects of magnetospheric plasma physics will be addressed by the comprehensive ISTP missions involving WIND, EQUATOR, POLAR, GEOTAIL, and CLUSTER, there are specific scientific objectives and measurements that are more limited and can only be addressed by Explorer-class missions of low-to-moderate cost. Recent examples include the Dynamics Explorers (DE) spacecraft, measurements from which have significantly advanced our understanding of magnetosphere-ionosphere coupling processes; and the Active Magnetosphere Particle Tracer Explorers (AMPTE), which investigated plasma entry into the magnetosphere via tracer ion releases in the solar wind. These and previous Explorer missions have been the mainstay of research in space plasma physics and their availability in the future is crucial to the development of this discipline.

Explorer missions in space plasma physics generally require orbits that are high (greater than 1 R_E) altitude and are intended to provide measurements over extended periods of time (greater than 1 year), i.e., not compatible with Shuttle or Space Station orbits. Potential missions have been studied by NASA in the past (e.g., Plasma Turbulence Explorer) but have not been carried out because of budget limitations. Other illustrative mission concepts are given in the report *A Strategy for the Explorer Program for Solar and Space Physics*, NAP, 1984. Among these missions are spacecraft to study

- acceleration at heliospheric shocks,
- magnetopause structure and dynamics,

- active plasma injection (seeding) experiments, and
- ionospheric instabilities and turbulence.

These mission concepts represent only a few examples, and a solicitation of the scientific community through the AO process will undoubtedly produce a variety of mission ideas addressing first-class scientific problems. It should be noted that the instrumentation and spacecraft technology for the few illustrative missions given above is all within current state-of-the-art, and no new developments are necessary.

Active Experiments

Active experiments, where the environment can be perturbed with injections of particles, beams, or waves and then studied to determine its responses, are a unique opportunity to perform laboratory-style experiments in space. Such experiments are extremely valuable in aiding our understanding of basic plasma processes because the experimenter has a great deal of control of the experiment and can therefore address sharply focused questions. Experiments in this category include the following:

Combined Release and Radiation Effects Satellite

Combined Release and Radiation Effects Satellite (CRRES) is a free-flying spacecraft mission undertaken jointly by DOD and NASA. The NASA portion of the mission involves chemical release experiments solicited by an AO, evaluated by a peer review committee, and selected by NASA/OSSA. This chemical release program is designed to replace partially the cancelled Chemical Release Module program, and has research goals consistent with those in the Kennel report.

CRRES is a two-part mission. The spacecraft will be launched initially into a low-Earth-orbit (LEO) where it will remain for a period of 45 to 90 days. During LEO, selected chemical releases will be carried out at specific locations designed to be observable from suitable ground-based diagnostics facilities such as the Arecibo and Jicamarca Observatories or high-altitude ground sites in the southwestern United States, as well as by aircraft-borne instrumentation.

The CRRES payload will include the following:

- *tracer experiments* in which releases of foreign elements can be used to trace geomagnetic field lines, assess natural electric fields and potential structures, and measure winds;
- *modification experiments* involving massive releases that can significantly perturb the ambient ionosphere; and
- *simulation experiments* in which releases are used to simulate plasma physical phenomena not amenable to laboratory experimentation.

Once the CRRES is transferred to a geostationary transfer orbit, several high altitude releases will occur. These releases are primarily for tracing magnetic field lines and for modifying the immediate region at low latitudes just at the plasmapause.

Tethered Satellite System

The Tethered Satellite System (TSS) is a joint project for NASA and Italy's National Research Council. NASA is responsible for producing the Shuttle-borne deployment mechanism and tether, while the Italian National Research Council is to furnish a satellite system to carry scientific experiments attached to the tether. The tether may be either a conductor or insulator, depending on the type of scientific mission. It can be utilized to study electrodynamic processes in the ionosphere or atmospheric phenomena in regions down to 130 km where few measurements have been made and are difficult to achieve by other means (rockets or satellites). Here we discuss only the conducting tether missions and refer to Chapter 9 for discussion of atmospheric tether missions.

Two electrodynamic tether missions are planned, TSS-1 and TSS-3. TSS-2 is to be an atmospheric mission (see Chapter 9). TSS-1 is planned for a mid-1987 Shuttle launch, TSS-3 to fly about mid 1990. These missions will be in a nominal 28° inclination orbit at 300-400 km altitude. On TSS-1, the conducting tether and its attached satellite will be deployed upward to a distance 20 km above the Shuttle. The tether will be attached to the conducting surface of the satellite, and through an electron gun to the orbiter's ground plane, to return electron current to the ionospheric plasma. The entire duration of the TSS-1 test will be 36 hours. Scientific experiments will be limited on TSS-1, which is an engineering test of the TSS, while TSS-3 is planned to carry a more sophisticated scientific payload.

The objectives of TSS-1 and TSS-3 are the following:

- determine the current/voltage characteristics of the system at high voltages;
- study management of electrical charge on the orbiter;
- produce Alfven waves in the ionosphere using the tether current source;
- produce LF ($<$ 1 kHz) waves by modulations of the tether current and study their propagation;
- study nonlinear plasma physical processes in the dynamic sheath around the satellite; and
- utilize the conducting tether as an efficient antenna for transmitting diagnostic VLF waves to distant receivers.

Shuttle/Spacelab Programs

The Shuttle/Spacelab capabilities are especially suited to accommodate active experiments, since they are massive and have energy, power, and heat rejection requirements that exceed the usual capabilities of unmanned free-flyers. Of particular interest is the use of this carrier to perform active experiments in which electromagnetic wave energy, energetic charged particle beams, plasmas, and neutral gases, and controlled releases of various chemical species are effected during 7- to 9-day missions. In addition, these instruments can be reflown on subsequent Shuttle missions in either their original form, or refurbished or upgraded as results from previous flights may dictate.

An attractive use of such Shuttle/Spacelab missions is also apparent: active experiment instrumentation can be developed in an evolutionary fashion, using the Shuttle/Spacelab flights as test beds for development of instruments in a form for later use in the Space Station and/or associated platforms similar to the STO. Such equipment as that used to inject large amounts of electromagnetic wave energy into the ionosphere and magnetosphere, or inject powerful electron or ion beams into those regions, can benefit greatly from on-orbit residence times much greater than the 7 to 9 days available on Shuttle missions, but an orderly program of preliminary developmental flights on the Shuttle would allow final development of a flight-qualified inventory of such equipment for use in plasma physical, magnetospheric, and ionospheric research on a station or platform of several months to a year mission duration. The effects of these active experiments can be diagnosed with near-by probes and through the constellation of magnetospheric free-flying satellites from programs such as ISTP and the Explorers.

Spacelab-2

Spacelab-2 (SL-2) is a multidisciplinary mission carrying 12 PI-class experiments on a nominal 7-day mission planned for launch in April 1985 into a 50° inclined orbit. Three SL-2 experiments are plasma physical or ionospheric in nature. The VCAP experiment involves an electron gun capable of pulsed operation up to 500 kHz at peak currents of 0.1 A at 1 kV. It also has diagnostics, including a capacitive probe to measure orbiter charge states, and can carry out orbiter charge management experiments. A free-flying Recoverable Plasma Diagnostics Package (RPDP) will measure electromagnetic interference levels in and around the orbiter cargo bay, diagnose effects of the VCAP electron beam (waves and particles), and perform wake and sheath measurements near the orbiter (up to 1 km separation). A third experiment uses dedicated engine burns of the Shuttle's Orbital Maneuvering Subsystem (OMS) in a series of active experiments for plasma depletion studies in ionospheric and radioastronomical areas. The primary diagnostics employ ground-based radars and optical imaging systems.

Spacelab Reflight Missions

A series of reflight opportunities utilizing existing Spacelab instruments can be exploited. An example is the EOM-1 mission, on which it is planned to carry the Japanese SEPAC instrument and the diagnostic AEPI instrument to support it, both flown on SL-1. These instruments will carry out electron beam injections and observations associated with geomagnetic field line tracing, electrical potential structures, beam-plasma discharge phenomena, artificial auroral displays and neutral or plasma gas injections. Other reflights-of-opportunity should be planned or identified.

Space Plasma Lab Program

Space Plasma Lab-1 (SPL-1) is planned for a launch on a near-polar (77°) orbit at about 350-500 km in December of either 1988 or 1989, depending upon budget constraints and development schedules. It is to carry a wave injection instrument with capability to radiate VLF from 1 to 30 kHz with up to 1 kW power input to a dipole antenna of length between 100 and 300 m. A Canadian-furnished HF transmitter and receiver will transmit and receive sounding signals between 100 kHz and 30 MHz. The SEPAC instrument from SL-1 will perform electron beam injections, with the AEPI instrument to support it with optical observations and a set of newly developed plasma diagnostics (TEBPP). To support the active experiments by making in situ measurements at predetermined distances along magnetic field lines connecting to the orbiter, a RPDP will be flown.

The scientific objectives of SPL are to

- test the ability of a dipole antenna in the ionospheric plasma to radiate VLF wave energy;
- study the nonlinear plasma physical phenomena around the high-voltage dipole antenna;
- study wave-particle interactions in the trapped electron population produced by VLF signals from an antenna above the F-layer maximum;
- perform VLF propagation studies for all paths possible out to 100 km from the orbiter and including radiation to ground stations;
- perform bistatic HF sounding measurements with orbiter and RPDP receivers to study ionospheric irregularities, travelling ionospheric disturbances, and coupling to gravity waves;
- perform high-current, high-voltage electron beam experiments and study the beam-plasma discharge and artificial auroral displays;
- perform field-line tracing and electrical potential structures diagnostics using the electron beam from SEPAC; and
- perform Shuttle wake and sheath measurements, antenna radiation efficiency estimates, electron beam evolution, and OMS thrusher firings diagnostics using the RPDP, AEPI, and ground-based instrumentation.

Space Station/Platform Programs

The Space Station/Platform capability provides an ideal vehicle for missions involving the active experiments using energetic particle beams, wave energy injections, and chemical releases. The capability to recover, service, and change out scientific experiments on-orbit opens new possibilities for experimentation using these heavy, power consuming experiments that can benefit from extended mission durations in low-Earth orbits.

It is desirable that such active instrumentation be developed in an evolutionary manner using earlier Shuttle/Spacelab flight opportunities for test-bedding and check-out.

Since the Space Station architecture (including the question of inclusion of one or more science platforms) remains to be determined, only general statements can be made. One can suggest missions up to 6-months duration on platforms that provide up to perhaps 25 kW of power, with energy storage units capable of furnishing high-peak-powers for pulsed operation of active experiments. Platforms in near-polar orbit would be ideal for wave and beam injection, while lower inclinations may be useful for missions involving the TSS. A comprehensive study of possible missions and payloads can be found in the final report of the science study group: *Solar-Terrestrial Observatory*, October 1981, and in *Solar-Terrestrial Observatory: Conceptual Design and Analysis Study*, April 1982, both NASA Marshall Space Flight Center documents.

The objectives of an STO-like Space Station Platform are to increase the understanding of wave-particle processes; magnetospheric-ionospheric mass transport; the global electric circuit; ionosphere irregularity structure, travelling ionospheric disturbances, and their coupling to atmospheric gravity waves; electrodynamic tether interactions including Alfven, magnetosonic, and plasma wave production; non-linear plasma physics; beam-plasma interactions; and plasma physics experiments in microgravity and without walls.

The latter area is of special interest, and should be examined carefully. There are laboratory plasma experiments that can be defined ideally but not carried out on Earth because of the presence of chamber walls. Some of these are related to the fusion energy program. For example, storage rings could be formed taking advantage of zero-gravity to eliminate support structures that represent plasma sinks or contribute unwanted impurities into the experimental plasma. A set of plasma physics experiments should be identified and examined for possible performance in a Space Station facility.

Suborbital Programs

The suborbital programs have traditionally included balloon, rocket, and aircraft systems. For some types of measurements these programs are appropriately being supplanted by Shuttle and Space Station programs. However, there are measurements of the stratosphere, middle atmosphere, and ionosphere for which the maintenance of vigorous suborbital capabilities is desirable and, indeed, imperative for the unique capabilities not achievable with Shuttle or satellites.

Balloon payloads can measure atmospheric electric fields and atmospheric potentials. Payloads for magnetosphere studies can include bremsstrahlung X-ray sensors, photometers, and even neutron (or other) sensor systems. Balloons also provide an inexpensive way to test new instrument concepts. Furthermore, a relatively long duration set of measurements can be made in a nearly constant location in latitude, longitude, and altitude. Correlations with ground radar and with spacecraft measurements in this way have proven very efficacious.

Similarly, rockets provide unique advantages in terms of specific local measurements at relatively low cost and low risk. Developmental testing of spaceflight hardware can be accomplished readily on rocket flights. Furthermore, many auroral studies and active experiments (e.g., beam experiments, chemical releases) can be accomplished most cheaply and most readily through rocket campaigns.

Finally, aircraft facilities can also be a valuable asset. Aircraft are utilized to measure electric fields associated with weather systems, for example. Also, testing of optical systems in safe and inexpensive ways is possible. Such testing can be most helpful in preparation for full spaceflight development work. Rapid deployment capability is also an attractive feature of aircraft facilities.

In summary, we recommend the maintenance of a strong suborbital program where it makes scientific, technical, and financial sense. Those programs that can use Shuttle capabilities effectively should be encouraged to use the Spartan and Hitchhiker systems, for example, but where scientific objectives can be achieved effectively, expeditiously, and at lower cost by use of balloons, rockets, or aircraft, these alternatives should be provided.

At present there is a funding level of approximately $3M for rocket and balloon payload in the space plasma physics budget. As illustrated in our budget timeline, we recommend that this level be increased modestly (to about $4M) through FY 88 and then be decreased. We recommend that the Spartan program be funded at the $2M level in FY 85 (in part with funds otherwise allocated to the rocket program). We then suggest that by FY 87 there be a constant level of funding, at about $4M/yr, through the mid 1990s in the Spartan program and an equivalent amount for the Hitchhiker program.

Planetary Magnetospheres

Studies of the plasma environments of other planets can yield data relevant not only to planetary science but also to understanding Earth's environment in broad scientific terms.

Magnetospheric structure and dynamics depend upon many aspects of the interaction between an object and its environment.

The planet or other central body (we include moons embedded in corotating planetary plasmas) may be unmagnetized (Venus, possibly Mars, major moons) or magnetized (Mercury, Jupiter, Saturn, possibly Mars and/or Io); may lack an atmosphere (Mercury, Ganymede, Europa, Callisto) or have an atmosphere (Venus, Mars, Jupiter, Saturn, Io, Titan); may be embedded in sub-Alfvenic flows (Io), near-Alfvenic flows (Titan), or super-Alfvenic flows (all others). There may or may not be secondary plasma sources such as Io's volcanoes or Saturn's rings within the magnetosphere. Rotation may be slow enough to be ignorable (e.g., Mercury) or may dominate dynamical behavior (e.g., Jupiter). For each combination of parameters, the relative importance of different physical processes changes, and spacecraft measurements can provide unique insights.

Mercury's magnetosphere is small, even on the scale of the planetary radius, because its magnetic field can barely stand off the solar wind. Yet there is evidence that substorms and particle acceleration occur at Mercury much as at Earth. Data from two flybys raise questions (e.g., what is the nature of hydromagnetic flow in a magnetosphere so small that an ion Larmor radius is not negligible?) but do not give answers.

Venus missions have illuminated the way in which solar wind plasmas interact with dense ionospheres. The solar wind magnetic field drapes around the ionosphere, and some magnetized plasma convects into the ionosphere, producing spatially confined regions of large, twisted magnetic fields (flux ropes) deep inside the ionosphere. Magnetic flux tubes couple ionospheric plasma to the solar wind and provide direct paths for particle losses from the ionosphere.

Past missions to Mars have not yet combined appropriate fields and particle instrumentation and spacecraft trajectories for studies of the magnetosphere. Thus, it remains uncertain whether Mars has an intrinsic magnetic field or not. Some think that Mars represents an important "intermediate" case, standing off the solar wind partly with a magnetic field (like Mercury) and partly with an ionosphere (like Venus).

Jupiter's large magnetic field, rapid rotation rate, and internal plasma source, Io, is radially distorted into a disc-like configuration modulated at the 10-hour rotation period. Indeed, the 10-hour modulation and control by Io of radio frequency emission probability were first noted by Earth-based observers. Those observations were confirmed in situ and features of the Jovian environment (magnetic field magnitude and direction, existence of field-aligned currents) inferred from remote observations proved remarkably accurate. The Galileo mission, to reach Jupiter in 1988, will permit an orbiting spacecraft to monitor the temporal variability of Jupiter's giant magnetosphere. In addition, Galileo will traverse the regions in which the Galilean moons form secondary magnetospheres within the rotating Jovian plasma, thus extending studies of comparative magnetospheres.

Saturn has a magnetosphere much like that of Earth, but modified by embedded moons and rings. Radio frequency emissions from Saturn are modulated at the planetary rotation period, but there is no evidence for asymmetries needed to explain the modulation.

Insights gained from studies of magnetospheres of other planets are of great importance to our evolving understanding of space plasmas. The next steps in planetary exploration should include the following:

- a Mars orbiter instrumented for fields and particles investigations, with orbits optimized for magnetospheric measurements;
- a Saturn orbiter with trajectory selected to allow high latitude measurements from which field asymmetries and radio sources can be investigated;
- a spacecraft placed in orbit about Mercury, the only known magnetized planet without an atmosphere, to illuminate the role of atmospheres in substorms and other magnetospheric processes; and
- exploration and intensive study of the inner Jovian system—density, composition, and energy of the magnetospheric particles; large-scale structure and rotation, time-dependent phenomena and relation to Io, other satellites, and orbiting gas and plasma; auroral activity on Jupiter; and electromagnetic emissions. [This objective, from the Space Science Board's Committee on Planetary and Lunar Exploration report,

A Strategy for Exploration of the Outer Solar System (in preparation), is endorsed by the CSSP].

Comets

The exploration of comets is a step into a new regime of space plasma physics in which a flowing magnetized plasma interacts with a dilute neutral gas in the presence of a source of ionizing radiation. Ground-based observations and satellite-based remote sensing of cometary plasma still have many unanswered questions about

- the range of physical mechanisms responsible for the rapid ionization of the gases released from the nucleus;
- the mechanism(s) responsible for the pick up of newly ionized material by the solar wind (i.e., acceleration and thermalization of the cometary ions and the deceleration and heating of the solar wind);
- the details of the mechanisms responsible for acceleration of plasma into the ion tail;
- the magnetohydrodynamic topology of the interaction region (e.g., Is there a thin or a thick ionopause? Are there flux ropes? Is there a shock internal to the ionopause?); and
- the interaction between plasma and dust.

A series of cometary exploration missions have recently been initiated.

- The International Cometary Explorer will fly through the tail of comet Giacobini-Zinner in September 1985.
- A series of five spacecraft will pass sunward of the nucleus of comet Halley in March 1986. One of these spacecraft, ESA's Giotto, is planned to pass close enough to the nucleus to penetrate the ionopause (if such an identifiable structure exists) and very briefly sample the cometary ionospheric plasma.
- A mission to rendezvous with a short-period comet is currently under study by NASA's Solar System Exploration Division.

The comet rendezvous mission offers the possibility of obtaining qualitatively different types of measurements than those that can be obtained with the flyby missions.

- It will be possible to study the evolution of the comet-solar wind interaction as a function of the level of cometary activity.
- It will be possible to *map* the major close-to-the-nucleus features of the comet-solar wind interaction in order to understand the major ionospheric processes such as ionization, acceleration, and heating of the plasma, which ultimately forms the tail.
- It will be possible to determine the abundances and velocity distribution functions of the minor as well as the major ion species in the inner coma where the local chemical composition is determined by ion-neutral reactions. Measurement of the electron temperature is also vital to understanding the inner-coma chemistry.

In view of the important and essential plasma physics that can be learned on a comet rendezvous mission, such a mission should include instruments for the measurement of plasma parameters—at a minimum, an ion mass-velocity spectrometer, an electron spectrometer, a magnetometer, and a plasma wave analyzer.

Theory and Modeling

NASA's Solar-Terrestrial Theory Program (STTP), initiated in response to the Colgate Report, has been one reason why solar system plasma research has reached a new level of precision, whereby it is strongly contributing to both general plasma physics and to the interpretation of space data.

Although this program has resulted in substantial progress toward the goal of assimilating our accumulated knowledge into comprehensive theories, several important problem areas remain. The level of support of particle acceleration as a generic topic with application to almost every area of space physics research is incommensurate with its prominence and the available theoretical knowledge and tools. The same is true for particle confinement and transport. It is worth noting that while over 50 active beam injection experiments from rockets and the Shuttle have been performed, the theoretical effort to interpret these results has only just begun. As a result, the subject of controlled beam experiments is scientifically behind, despite the enormous progress in the understanding of natural beam and radioemission physics. A newly emerging area that needs attention deals with neutral gas plasma interactions including the effects of large structures. Research on these topics is a must in the era of cometary exploration and of space station research. A major increase in funding is immediately necessary for these high-leveraged scientific investigations.

Specific theoretical problems may be identified that are too complex to be addressed with current funding levels and whose solution within a specified time period is judged important. A concerted theoretical attack on such problems should be approached through the use of an AO or a "Dear Colleague" letter, by which one or more groups should be chosen and funded. Computer time should be made available to these groups on national computer facilities, and support provided for their additional manpower needs. The subject of energetic beam injection in space is a potential example: by collecting the many experimental results produced over the years and utilizing the computational theoretical tools available, the scientific return to the tens of millions of dollars spent on experimental investigations over the years can be substantially increased at a total cost of less than $1M/yr.

Mission Operations and Data Analysis

The scientific value of space missions comes, quite obviously, from the data that are returned and processed through ground systems. Hence, a primary consideration of space programs has to be the proper planning of data systems from the earliest stages. Equally important is the recognition that scientists—the true users of the data—should be involved in all phases of the planning and implementation of data systems.

Many space plasma missions have continued to operate well beyond the primary mission phase. Funding in the MO&DA program must therefore be provided with the recognition that the data from the extended mission period are an extremely important scientific asset. These data provide the basis for testing the hypotheses developed during the primary mission phase.

Because of the wealth of scientific data provided by space physics missions and because of the inherent need for correlative analyses, the space physics community has been a leader in improved data analysis techniques. In fact, the Space Physics Analysis Network (SPAN) system has grown out of the need in the space plasma community to merge, correlate, and intercompare very diverse data sets. SPAN arose from a "grass roots" effort among space physicists and now is leading virtually all NASA disciplines in scientific data interchange and in the associated development and implementation of networking, graphics standardization, and data formatting techniques.

Based upon the direct "hands on" experience provided by the SPAN system, programs such as ISTP and UARS are developing data facilities around well-tested concepts of data handling and data processing. Superior, cost-effective scientific return will result within these new programs. Existing and future programs of other types will benefit from this continuing experience. We recommend that increased MO&DA funding be provided to allow data archiving and cataloging, improved networking, and enhanced analysis capability in a discipline with proven experience, capability, and networking infrastructure.

Research and Analysis

Funds associated with individual space missions increase and decrease on relatively short time scales whereas the training, assembling, and maintenance of scientific teams is, and should be, a much longer term activity. The expertise and capability of a scientific staff must be continued and nurtured in order to allow progress in basic research. The kind of long-term stability in funding that leads to real success in the space sciences comes about from the R&A funding program.

Analyses have shown an alarming decrease in the R&A funding in space plasma physics. In terms of constant FY 84 dollars, this decrease has amounted to $4M from $15M to $11M between FY 78 and FY 84. In order to restore an appropriate level of funding R&A, and in order to establish a more proper balance of R&A among the space sciences disciplines, we recommend an increase from $11.5M in FY 85 to $16M in FY 86. From FY 87 forward we strongly recommend a level of about $20M in space plasma R&A funding.

An area requiring particular attention in space plasma physics is advanced instrument development. If one relies solely on funding associated with new missions to provide instrumental design improvement (and innovation), then hardware progress will be unacceptably inadequate. We recommend that NASA provide a vigorous program of R&A support explicitly earmarked for instrument development including new detection techniques, improved onboard processing capabilities, higher spatial and temporal resolution, and other instrument improvements.

Technology Requirements/Instrument Development

It is evident from the description of the recommended missions that current spacecraft technology is adequate in all cases to carry out the program. Recent advances in microprocessor systems and custom-made VLSI chips suggest that onboard data processing techniques may well result in acquisition and evaluation of much larger volumes of data than previously thought possible, without a consequent increase in data rates transmitted to the ground. Incorporation of reliable data storage devices aboard spacecraft will minimize requirements for continuous tracking coverage by the Deep Space Network (DSN) [for spacecraft in orbits that cannot use Tracking and Data Relay Satellite System (TDRSS)], thereby decreasing costs in manpower and facilities for data acquisition.

Science instrument development, on the other hand, is an ongoing process. Funding for such development is included in the recommended R&A program, except in those cases where major, facility-class instruments are required to carry out any of the missions recommended for space plasma physics. Nevertheless, science from missions later in the timeline is likely to be enhanced by the development of more advanced instruments and techniques, as they become available.

Long-Term Studies

Mission objectives are typically restricted to those attainable within a few years, yet in studies of solar cycle variations and other long-term changes of magnetospheric properties, it is crucial to monitor key regions of the magnetosphere over long periods of time. For this purpose, geostationary satellites are particularly well suited; it is essential that scientific instrumentation be provided on geostationary satellites or Space Station Platforms for continued monitoring of fields, particle fluxes, and plasma composition over many solar cycles.

Priorities

The highest priority for magnetospheric plasma physics is clearly the ISTP program. The other recommended missions of the space plasma physics program are a healthy and diverse mix of free-flyer spacecraft and active experiments. The elements of the program are dictated by the overall discipline funding profile and integration with the phasing of Shuttle, Space Station, and other capabilities.

The rededication of a vigorous Explorer program is imperative to perform small-to-moderate cost, specialized missions in solar and space physics that complement the major magnetospheric plasma physics missions represented by ISTP spacecraft.

On a comparable level are missions to carry out the programs that will lead to evolutionary production of active experiments for use in the Space Station era. These are the Shuttle/Spacelab and Tethered Satellite System programs, including SPL, SL reflights such as EOM-1, and the TSS-1 and -3 missions.

Strong MO&DA and R&A programs and mission-directed theory and modeling efforts must be inseparable components of the above flight missions. These programs must be supplemented by stable programs supporting more general R&A and space plasma physics theory and modeling.

Space Station/Platform missions are long-term but have a priority set by their timeline. Development of the active experimental instrumentation should proceed so that it can be easily retrofitted to Space Station use.

MAGNETOSPHERIC/PLASMA PHYSICS

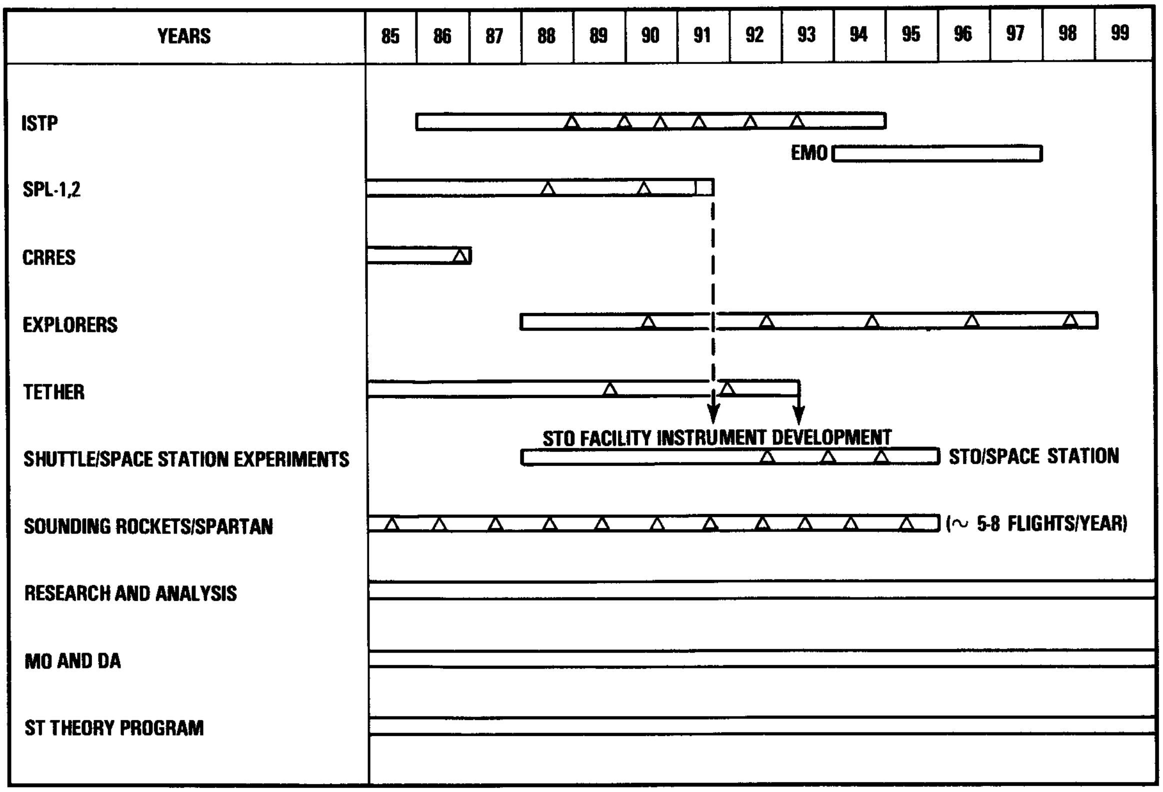


FIGURE 6

Suborbital programs have not been prioritized here. It is assumed that a steady level of funding will be provided by which these small programs-of-opportunity can be supported as they are identified and defined. CRRES and SL-2 are not prioritized because they are approved programs.

New opportunities to provide frequent flight opportunities at relatively low cost are developing on the Shuttle through the Spartan and Hitchhiker programs. These programs should be encouraged and managed in the same manner as the sub-orbital program. New research ideas can be developed and tested by a larger segment of the community at rather low cost.

Figure 6 shows the timeline for the program in space plasma physics. There are several programs that we consider scientifically important but could not include in our timeline because of the funding constraints that we have imposed on this implementation plan. Most important among these are missions to study the magnetospheres of other planets (Mars, Saturn, Mercury), a comet rendezvous mission, and a heliosphere boundary probe.

9 DETAILED MISSION PLANS—UPPER ATMOSPHERIC PHYSICS

Introduction

The upper atmosphere is defined here as the region above the tropopause (about 12 km) and includes the stratosphere, mesosphere, thermosphere (and ionosphere), and exosphere. The program is constructed on the premise that this entire region should be investigated as one dynamic, radiating, and chemically active fluid. Historically, the upper atmosphere was investigated by remote observations of limited regions or layers. The satellite era led to intensive study of the Earth's thermosphere by in situ measurements. Complementary observations were obtained with sounding rockets and ground-based incoherent backscatter radars.

In-situ measurements of the stratosphere have been made by balloon-, rocket-, and airplane-based instruments whose flight durations are short, and the resulting data are restricted in geographic coverage as defined by their trajectories or launch locations. Rockets, for example, have provided limited knowledge of vertical structure in composition and temperature at isolated locations. Recently, ground-based capability to probe these regions have been demonstrated by MST radars and lidar, but again at only a few locations.

To gain a global perspective of the upper atmosphere in both horizontal and vertical coverage and investigate the upper atmosphere as one interactive fluid, comprehensive remote sensing measurements from space platforms are the major directions for the future. Thus, the upper atmospheric physics program was designed around the Upper-Atmosphere Research Satellite (UARS) spacecraft—one of the principal recommendations of the Kennel report.

Another area of upper atmospheric study is solar-terrestrial coupling, which is concerned with the response of the Earth's magnetosphere, ionosphere, and atmosphere to solar inputs and their variability. Studies of solar-terrestrial phenomena are of considerable practical importance and provide an incentive for coordination of individual programs in solar physics, magnetospheric/space plasma physics, and upper atmospheric physics to achieve a better understanding of the effects of solar cycle, solar activity, and solar-wind disturbances upon the Earth's atmosphere from the thermosphere down through the troposphere.

Program Descriptions

Major Missions

The highest priority in observatory-class missions for the 1980s has been the Upper-Atmosphere Research Satellite (UARS), now a new start in FY 85. It will provide, for the first time, an almost global data set on the chemistry, dynamics, and radiative inputs of the 10 to 70-km region of the atmosphere, i.e., the stratosphere and lower mesosphere, although some instruments are capable of useful measurements to an altitude of approximately 200 km (Figure 7). The goals of the UARS program are to understand the mechanisms controlling middle atmospheric structure and processes, to understand the response of the upper atmosphere to natural and human perturbations, and to define the role of the upper atmosphere in climate and climate variability. To accomplish these goals, several areas of scientific study will be fostered by the mission, including energy input and loss, global photochemistry, dynamics, coupling among processes, and coupling between the upper and lower atmosphere. The UARS data will be critical in evaluating the extent of ozone depletion caused by human activities and the impact of upper atmosphere processes on climate change.

The instrument payload has been carefully selected to meet the goal of coordinated and complementary global measurements of ozone, temperature, pressure, energy input, winds, and chemical trace species by remote sensing. A broad complement of stratospheric constituents will be

UPPER ATMOSPHERIC PHYSICS PROGRAM

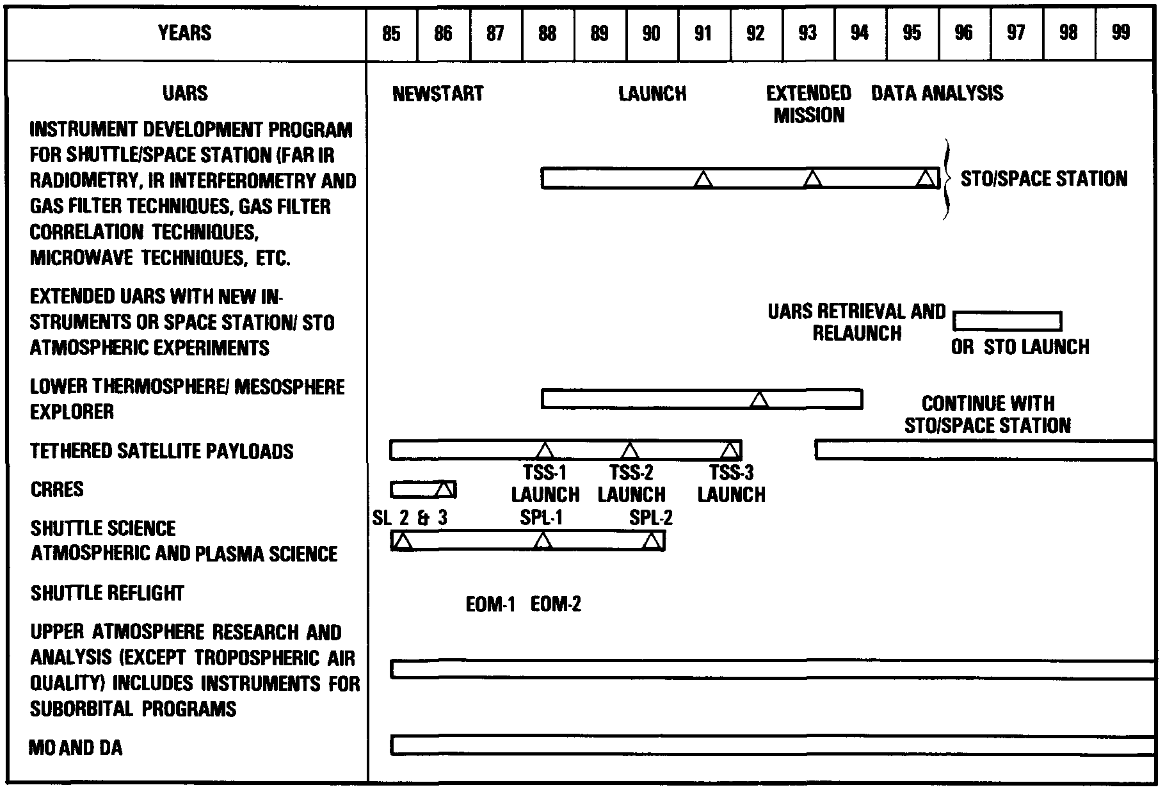


FIGURE 7

measured as part of the UARS payload. Many of the important free radical species (ClO, NO_2) will be measured simultaneously, as well as ozone densities. Further, most of the long-lived species (e.g., CH_4, N_2O, CF_2Cl_2) that are the source of these radicals will also be observed.

It is well known that stratospheric ozone and other stratospheric trace gases are dependent not only on photochemistry, but also on atmospheric dynamics. Perhaps the most important aspect of the UARS mission is that direct measurements of atmospheric winds will be made simultaneously along with the photochemical observations, so that the interactions between photochemistry and dynamics can be examined better than from previous satellite missions where only temperature was measured.

The UARS program includes theoretical studies and model analyses with theoretical principal investigators as an integral part of the program to complement the measurements and data analyses. Through this coordinated program in measurements, data and model analyses, and theoretical investigation, it is anticipated that substantial progress will be made in solving the outstanding physical and chemical problems above the tropopause.

UARS will be launched in the fall of 1989 using the Shuttle, which will deliver it directly to the operational circular orbit at 600 km and inclined 57° to the Equator. At this altitude and inclination the remote sensors looking 90° to the spacecraft velocity vector can see to 80° latitude, providing nearly global coverage. The inclination of the orbit plane also produces a precession of the plane to allow all local solar times to be sampled in about 33 days, which should give resolution of diurnal atmospheric effects in a period that is short relative to seasonal effects.

The UARS spacecraft can be retrieved by the Shuttle and is designed to be refurbished, thus allowing for an extended UARS mission. For an extended mission, new remote sensing instruments developed under the instrument development program (discussed below) to investigate the same and/or another region of the atmosphere could replace the existing instruments. Since the selection of the UARS instruments, technology has advanced sufficiently that it is now possible to remotely sense key radicals (e.g., HO_2) that play a critical role in the photochemistry of the middle atmosphere. These measurements should have high priority on an extended UARS mission.

The UARS objectives include the need for coverage of seasonal phenomena, probably requiring at least 3 years of observation. The planned first mission of 18 months will not fulfill this requirement, and an extended mission is therefore highly desirable.

UARS also could be inserted in a high inclination (polar) orbit for its extended mission and accomplish the global coverage as originally proposed for the second spacecraft of the UARS mission. High latitude phenomena are of particular importance in improving our understanding of global dynamics, chemistry, and particle inputs.

Alternatively, in this time frame (FY 94), the Space Station and/or STO may prove to be a better platform for remote sensing instruments. Current plans allow for considerable flexibility in selecting the best platform for remote sensing of the atmosphere in the late 1990s. Based on current projected UARS mission costs, an extended UARS mission would cost about \$270M in FY 85 dollars, assuming \$80M for new instruments.

Explorers

The Explorer Satellite program has been essential to the development of upper atmospheric physics, as evidenced by the important contributions from AE, SME, and DE (Chapter 6). In the solar-terrestrial context, perhaps the most important region of the atmosphere is the mesosphere and lower thermosphere where electric fields and particles from the magnetosphere deposit most of their energy. These energy inputs cause significant perturbations to the chemistry, dynamics, and thermal structure of the lower thermosphere and can also propagate to the other regions of the atmosphere. For example, as discussed in the Kennel and Explorer reports, it is known that nitric oxide (NO) can be produced in the lower thermosphere by aurorae and solar proton events and subsequently be transported down into the mesosphere, and possibly into the stratosphere where it can affect stratospheric ozone concentrations. Another result of energy deposition is thermospheric heating during geomagnetic storms that drives an upward expansion of the neutral atmosphere, increasing satellite drag and causing global ionospheric perturbations via chemical and dynamical processes that are still poorly understood.

Because neither UARS nor ISTP missions will directly address these scientific questions, we suggest a mesosphere-lower thermosphere explorer (MELTER) to remotely sense the chemical, dynamical, and thermal response of the 70- to 150-km region to solar and magnetospheric perturbations. This region has been called the "ignorosphere" because of the great difficulty in measuring its properties. It is desirable that the MELTER mission occur simultaneously with the UARS and ISTP missions to acquire a comprehensive solar-terrestrial data base. Substantial cost savings are possible in this situation as critical instruments on UARS and ISTP would not have to be duplicated on MELTER. Although the complexity of the instrument payload will have to be limited, preliminary studies suggest that such a mission can be successfully accommodated within the guidelines for the Explorer Program as specified in our earlier report.

To study the dynamics and photochemistry of the mesosphere-lower thermosphere, measurements of the following geophysical quantities are important: winds, temperatures, concentrations of NO, O_3, O, and odd-hydrogen radicals, electric fields, particle precipitation, and tracers such as H_2O and CO. Since all of these quantities cannot be measured by a single Explorer satellite, a selection of quantities from this list must be made.

Another Explorer-class spacecraft is the Combined Release and Radiation Effects

Satellite (CRRES). This NASA/DOD joint effort will perform experiments in the solar-terrestrial system by means of active probing with injections of matter and energy. The research goals of CRRES are to provide a better understanding of the solar-terrestrial environment and also to study physical processes in the magnetosphere, ionosphere, and upper atmosphere. The scientific objectives, programmatic details, and recommendations regarding this mission are outlined in Chapter 8.

Additional Explorer missions will be proposed by the upper atmospheric physics community to investigate important scientific problems. One of the goals of the Explorer program is a quick-reaction capability to respond to mission targets of opportunity; therefore, we should not now attempt to predict what will be the most important scientific opportunities in the mid to late 1990s.

Space Station/Solar Terrestrial Observatory

Requirements for the Space Station Program are only now being defined, so it is difficult to present definitive plans for a scientific program. Nonetheless, the STO, which was recommended by the Kennel Report and studied in some depth by NASA, is compatible with the Space Station Platform from the perspective of upper atmospheric physics.

The STO is a problem-oriented instrument payload based on a platform approach, i.e., the payload is located on a space platform and is set in orbit, serviced, and retrieved by the Space Shuttle. The central scientific goal of the STO is to understand the physical processes that couple the major regions of solar-terrestrial space. This goal encompasses the solar atmosphere, the interplanetary medium, the Earth's magnetosphere and ionosphere, and the entire neutral atmosphere of the Earth.

The platform approach offers a unique combination of capabilities, different from those of both conventional free-flyers and Shuttle/Spacelab. The characteristics that are important for the STO are

- large Shuttle-class instrumentation,
- long duration in orbit,
- high power generation,
- regular in-orbit servicing, and
- multidirectional pointing.

The STO Science Study Group discussed eight representative solar-terrestrial scientific objectives that benefit from the platform approach and a program of measurements for each. These objectives are to understand

- solar variability,
- wave-particle processes,
- magnetosphere-ionosphere mass transport,
- the global electric circuit,
- upper atmospheric dynamics,
- upper atmospheric chemistry and energetics,
- lower atmospheric turbidity, and
- planetary atmospheric waves.

A two-stage approach to a multidisciplinary payload is proposed: an initial STO that uses a single platform in a low-Earth-orbit and an advanced STO that uses two platforms in differing orbits. Coordination of STO with an interplanetary companion, such as WIND or SOHO, would be highly desirable. In addition, properly planned and implemented operations, data handling, data analysis, and theoretical modeling must be treated as an inseparable part of the STO mission. With the characteristics outlined above, the Solar Terrestrial Observatory can make a unique and valuable contribution to NASA's Space Station program for solar-terrestrial physics and integrate the subdisciplines of solar and space physics into a true terrestrial program.

Spacelab/Shuttle Science

Scientific observations from the Shuttle have just barely begun. More frequent use of this platform for passive and active experiments is an absolute requirement. In the time line of Table 7 are indicated the launches of Spacelab 2 and 3, Space Plasma Laboratory 1 and 2, along with Shuttle reflights as part of the Environmental Observation Missions (EOM). Important atmospheric observations will be made during these missions even though atmospheric physics is not the primary driver for SL and SPL flights. These missions are discussed in more detail in the magnetospheric/plasma physics section (Chapter 8).

The payload for the first EOM uses five proven instruments from Spacelab 1, 2, and 3 missions in a continuing effort to monitor variations in the total solar irradiance and the solar spectrum with state-of-the-art precision and to characterize some of the atmospheric responses to changes in the incident solar energy. A series of flights is planned so that similar measurements can be made over a complete 11-year solar cycle.

The Tethered Satellite System (TSS) will provide an important new facility for conducting space experiments in regions remote from the Space Shuttle Orbiter. Payloads of 200 to 500 kg can be deployed to distances of 100 km and held in fixed position with respect to the orbiter by means of a closed-loop control system acting upon a tether. Data handling and command capabilities will permit active experiment interpretation and control by orbiter and Payload Operations Control Center (POCC) ground personnel.

The TSS is expected to open the way to several entirely new areas of long-term scientific experimentation not heretofore possible. For upper atmospheric physics these areas include

- direct observation of magnetospheric-ionospheric-atmospheric coupling processes in the 125- to 150-km region of the lower thermosphere and
- the in situ observation of important atmospheric processes occurring within the lower thermosphere.

We recommend continued development of the TSS for use on the Space Station/Platform missions. Multiple tethered satellite deployments would allow simultaneous measurements of the ionosphere and atmosphere at several altitudes and controlled electrodynamic perturbations of the ionosphere.

Achievement of polar orbital capability and long-duration use of Shuttle instruments are related goals toward which Shuttle operations should evolve in the 1980s. 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 also recommend that the time on orbit of Shuttle-class instrumentation be extended. Current Shuttle instrument development should be compatible with providing an eventual continuous presence in space of Shuttle-class instrumentation for solar-terrestrial research. NASA should consider use of existing low-cost payloads, with prime candidates being engineering models left over from SAGE and Nimbus 7 (e.g., SBUV, SAGE, SAMS, LIMS). These could be flown on Shuttle missions or, more preferably, on a longer term platform such as the European Shuttle-launched spacecraft (EURECA).

Theory and Modeling

Theory and computer modeling play a fundamental role in upper atmospheric and solar-terrestrial research. They are crucial in the identification of key observations that must be made to establish a correct understanding of the processes at work. Computer models are useful for simulating large systems, for testing the importance of competing coupling processes on a global scale, and for providing a framework within which large amounts of data may be analyzed.

In upper atmospheric physics, the 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 and the plasmasphere. Comprehensive models must take into account chemistry, energetics, and dynamics, because they are tightly coupled. In some areas, such as the non-LTE radiation budget of the upper mesosphere, current models are primitive and a substantial effort will be required. In others, where more complete understanding of composition, radiation, and dynamics currently exists, continuing interaction between model development and observation is the primary need.

The Solar-Terrestrial Theory Program (STTP) can contribute towards attaining these goals but additional effort and funds will be needed in the future for specifically upper atmospheric physics to complement the present modeling emphasis on the magnetosphere as well as our recommended experimental program.

Mission Operations and Data Analysis

As the Friedman-Intrilligator report, *Solar-Terrestrial Research for the 1980's*, pointed out, unprecedented amounts of scientific data have accumulated from past space missions. Data handling and management have become a problem due to a variety of factors: e.g., scattered location, incompatible formats, obsolete technology (see *Solar-Terrestrial Data Access Distribution and Archiving*, NAP, 1984). Planning efforts for several recent missions (e.g., AE and DE) and future missions (UARS and ISTP) have given careful consideration to the difficulties, and the trend is toward requiring experimenters to meet specified data-management conditions designed to speed up the data reduction time, to use common physical units and data formats, and to render the data base available to the scientific community rapidly and in a "user-friendly" form. Objectives to be met include the provision of immediate and remote access to data by principal investigators and their teams during a mission, similar remote access by the scientific community at-large as soon as proprietary requirements have been fulfilled, and timely and automatic acquisition of the data by the National Space Science Data Center in order to satisfy all archiving requirements and the future needs of the entire scientific community.

Currently, in years following the end of Explorer and observatory-class missions, funding levels have not been adequate to analyze and interpret much of the acquired data to its full potential. In order to meet the above goals and ensure that the principal investigators and scientific community at large have adequate resources to analyze their expensively acquired data, we recommend a significant increase in MO&DA funds. We do note that NASA has made a start in this direction with their stratospheric data analysis program.

Research and Analysis

The health of upper atmospheric physics depends crucially on long-term support of individual scientists, research associates, and graduate students. The Research and Analysis (R&A) funds provide the foundation of the creative and innovative research base and graduate education that has made the United States preeminent in space science. It is essential that sufficient funds are available to maintain strong research groups at universities, national laboratories, and private industry, which provide the scientific expertise and leadership to carry out the more ambitious efforts outlined in this report.

Technology Requirements/Instrument Development Program/Suborbital Programs

The upper atmosphere cannot be studied in isolation. The source molecules of critical importance to stratosphere chemistry (N_2O, CH_4) are produced in the troposphere by complex biological processes, some of which are certainly subject to anthropogenic perturbations (e.g., use of nitrogen fertilizers). Thus, effective study of the stratosphere must involve analysis of (a) exchange processes with the troposphere and (b) further study of biosphere-ocean-atmosphere interactions. To some degree, these can best be performed in the near term from aircraft and balloons with the development of instrumentation to measure gas abundances and fluxes. A global perspective will, however, require remote sensing from an appropriate space platform with advanced instruments.

A high priority should be given to funding advanced instrumentation development for upper atmospheric studies because the vitality of the field requires the continuous development of "state-of-the-art" technology. Technological advances are anticipated in detector arrays, electro-optical subsystem and component technology, onboard information processing, and cryogenic cooler development using both active and passive systems. These advances should impact the next generation science requirements and instruments for STO, Space Station, and/or the extended UARS Mission. Development and testing on sub-orbital platforms must be an integral part of such instrumentation advances. Exclusive of Shuttle launch and operations cost, a funding level of about $15M/yr is estimated as required for development of the next generation of scientific instruments through the demonstration test phase.

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. Further, the unique ability of rockets and balloons to measure small-scale spatial and temporal variability is essential to our understanding of middle-atmospheric transport processes. Balloons and rockets also provide in situ corroboration of remote-sensing spacecraft observations. In addition, only rockets can make in situ vertical profile measurements in the 40- to 120-km altitude region. Active experiments in the thermosphere and lower ionosphere are also most effectively conducted using rockets.

When the low cost, fast-turn-around Getaway Specials ("GAS CAN"), "Hitchhikers", and Spartan experiments become a reality on the Shuttle, we recommend a phase out of all non-in situ rocket experiments. We recommend the development and perfection of long-duration (2-4 weeks) balloons to carry out in situ and long-duration remote sensing measurements.

Planetary Atmosphere Studies

A thorough understanding of the evolution and behavior of our own atmosphere requires that it be viewed in the broader context of comparative planetary studies. We heartily endorse the SSEC recommended core missions that contain atmospheric exploration components: Mars Geoscience/Climatology Orbiter, Comet Rendezvous/Asteroid Flyby, and Saturn Orbiter/Titan Probe Missions. We also recommend the prompt implementation of the Mars Aeronomy Orbiter Mission after the completion of the initial core program. These intensive studies of other planetary atmospheres will complement our recommended program for the Earth's upper atmosphere. A detailed understanding of the photochemistry, dynamics, and energetics of these planetary atmospheres will provide a proper context to understand the complex interplay of chemical and physical processes in our atmosphere that sustain life.

Long Term Programs

Solar Constant

Radiative-balance climate models indicate that the Earth's surface temperature is 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 is an absolute necessity. Monitoring the solar spectral irradiance is highly desirable, because the ultraviolet part of the spectrum below 1800 Å is known to vary significantly (> 20 percent) with solar activity.

Long-term observations of solar spectral irradiance and solar-wind parameters are prime examples where there has been inadequate past commitment of resources and effort. Spectral irradiance monitoring has been recognized in the past as essential to ionospheric/magnetospheric research. However, these observations have been supported only in piecemeal fashion by various government agencies. No one agency is dedicated to the support of long-term monitoring of this type, and no one agency has devoted sufficient resources or interest in this area to do it properly. NASA is the suitable agency to assume responsibility for these observations, and it is our recommendation that NASA assign high priority to suitable instruments on space platforms over the next 15 years to acquire these extremely valuable data.

Monitoring of Ozone

Ozone is one of the most important atmospheric species because it is the only constituent capable of effectively absorbing biologically harmful ultraviolet radiation in the wavelength range from about 2500 to 3000 Å. Since the ozone layer's absorption at these wavelengths effectively protects life at the surface, the study of the stability of the ozone layer is of prime concern.

Our understanding of the ozone layer has evolved considerably over the last decade. In particular, refinement of our understanding of stratospheric photochemistry has led to substantial reductions in the estimated changes in ozone expected to result from chlorofluorocarbon releases. Current models predict maximum local changes near the 40-km level, with much smaller changes below. The total column changes are likely to be strongly dependent on dynamical and radiative feedbacks, because much of the total column resides at low altitudes (i.e., below 20 km) where ozone is controlled by dynamical processes. Model calculations indicate that the long-term response of stratospheric ozone to increasing chlorine abundances may be closely coupled to radiative feedbacks related to simultaneous increases in CO_2, N_2O, and other species.

Therefore, it is important to monitor ozone both at the 40-km level, where changes are predicted to be greatest, and at altitudes of about 10-30 km, where most of the total column is located. The methods currently being used for long-term monitoring of these regions are substantially different. At the 40-km level, observations are provided by ultraviolet sensors onboard satellites, which offer complete coverage, reasonable altitude resolution, and good climatology. The low altitudes (near 10-20 km) are not very accessible to ultraviolet satellite technology and are best addressed either by infrared remote sensing or perhaps by a concerted balloon program using optical in-situ or perhaps chemiluminescent sampling. An important problem, however, remains—that of satellite calibration. Since many of the available satellite measurements are subject to possible instrument drift, their accuracy may not be sufficient to conclusively detect changes of the magnitudes expected to be found in the 1990s. This highlights the need to develop accurate in-situ instrumentation for use in connecting satellite data. It is particularly important to improve current balloon instrumentation so that reliable soundings can be made at high altitudes.

Thus, a balloon program should represent an integral part of the future long-term program, both because of the dominant role of the lower stratosphere in the global total ozone budget, but also because of the need for calibration of satellite instruments. We recommend that NASA continue its program in monitoring ozone and improve calibration of future satellite data to meet accuracy requirements to detect predicted ozone changes in the 1990s.

Priorities

In Figure 7 the time line for the upper atmospheric physics program is presented. Priorities considered when constructing this time line were primarily funding constraints and already-approved new starts that NASA is committed to execute to completion. The FY 85 new start for UARS represents a major commitment of funds into the early 1990s.

Current NASA planning indicates that the Space Station will be available for scientific research in the middle 1990s. It is essential that appropriate instruments be developed to fully exploit its capability. An FY 88 start is thus essential for the instrument development program to provide the needed 5 years for development through flight testing on the Shuttle. An additional 2 to 3 years is required to select from the successfully developed instruments that should be built for long-duration use on the Space Station. In the event that the Space Station encounters difficulties similar to those that plagued the Shuttle program, we recommend the backup option of retrieving and refurbishing the UARS spacecraft. Scientific progress can thus be maintained.

The CRRES and Tethered Satellite payloads are approved missions along with SL-2 and 3, SPL 1 and 2, and EOM 1, 2, and 3 Shuttle flights. Funding constraints limit the new start of the MELTER mission in the Explorer program to FY 88 at the earliest. It would be highly desirable to launch this Explorer within 6 months of the UARS launch to obtain the maximum overlap in data coverage. For reasons previously noted, the research and analysis program is of utmost importance for the continued health of the field and therefore the maintenance of this budget item at the indicated levels is of the highest priority.

Although the detailed understanding of planetary atmospheres complements terrestrial atmospheric studies, we did not make specific recommendations in this area nor include it in our budget time line because of programmatic reasons. Nevertheless, we strongly recommend a continued and intense exploration of planetary atmospheres.

10 PERSPECTIVES

Introduction

Our intent in this chapter is to highlight several items that are important to the general health and conduct of our discipline. They are organized into this chapter because they are applicable to all of the subdisciplines (solar, plasma, atmosphere), they do not necessarily involve specific programs, and they are not explicity included in our recommendations. They are nonetheless, extremely important to the future of solar and space physics and need to be considered in terms of the broad context of NASA's role of conducting science in space.

Data Management

The management of space science data has not received the attention necessary to most effectively utilize this national resource. The problems of past and present data management systems and organizations were identified in CODMAC - Volume 1. The recent NAS Report, *Solar-Terrestrial Data Access, Distribution, and Archiving* (NAS, 1984), made recommendations for improved data management for solar and space physics. In particular, that report identified access to data as the main problem in the discipline and developed plans including a Central Data Catalog and Data Access Network to alleviate the problem. The report also recommended a pilot program, to be initiated by NASA's Information Systems Office, that would develop the detailed plans necessary for establishing the catalog and network. NASA has not yet acted on this recommendation. We believe that this pilot program is a necessary step for constructing the data system for the ISTP, the highest priority new program in solar and space physics, and we *urge NASA to implement the pilot study as soon as possible.*

International Cooperation

At a recent meeting of scientific representatives of the United States and Western Europe, organized by the U.S. Space Science Board and the European Science Foundation's Space Science Committee, (*An International Discussion on Research in Solar and Space Physics*, NAS-ESF, 1984), the conferees recommended that an international program in solar and space physics be established to address the mutual scientific objectives of this discipline.

This conference was valuable not only in attempting to structure an integrated program of scientific activities directed at specific goals, but also in enabling the two communities to discuss, frankly, scientific, programmatic, and institutional issues. Such conferences are therefore important as forums for the exchange of views at the level of working scientists and should be expanded in the future to include other communities interested in this area of research, most notably, Japan.

The ISTP Program as currently planned is certainly responsive to the recommendation. We emphasize, however, that the science objectives are the essential goal to accomplish—if, for any reason, the international agreements for missions to address these objectives cannot be implemented, the present plans will have to be modified so that the science objectives can be accomplished.

Mission Costs

The issues concerning costs of space science programs are particularly difficult for scientists to address because of their limited engineering, project management, and accounting expertise. Nonetheless, such issues are important to scientists because high program costs or low budgets lead to situations where access to space becomes impossible.

Several of these issues, discussed in turn below, are

- assessing program costs for planning purposes,
- controlling mission costs, and
- maintaining basic research capability within a mission-oriented environment.

Planning

In establishing future program priorities based upon cost and budget projections, there is some risk that the projections are not completely accurate. Such is the case for this report. While we have attempted to obtain the best possible information on program costs, we realize that they are, at best, only estimates and are likely to change as project definition proceeds. *Thus, our approach of establishing temporal priorities is, we believe, still valid because the mission sequences and program emphasis are based on relative costs compared to a reasonable budget allowance.*

Controlling Costs

Although the responsibility for controlling program costs belongs, rightly, to NASA managers, scientists are concerned about such matters because space research depends directly on funding allocations. Since the costs associated with space research are inherently high, it is important to attempt experiments and to develop approaches aimed at reducing costs. Our Committee recently identified a few ideas that we believe would prove useful in reducing costs of Explorer missions (*A Strategy for the Explorer Program for Solar and Space Physics*, NAS, 1984). These ideas included the following:

- reducing mission complexity by focusing on specific, sometimes limited, science objectives;
- providing budgets large enough to keep development times reasonably short, thereby avoiding the cumulative effects of inflation;
- more thoroughly preparing for high-risk technological development;
- adjusting reliability and quality assurance controls to suit program objectives and to achieve realistic risk/cost tradeoffs; and
- using more standardized or commercially available hardware.

While these suggestions were made specifically for NASA's Explorer Program, we believe that they may well be more generally applicable. We urge NASA to consider these approaches and to work to develop others that will reduce the costs of space missions and thereby make the whole enterprise of space research more effective.

Research Base

Because NASA is a mission-oriented agency where success is frequently measured in terms of flight programs, basic research capability rarely receives high priority attention. If the funding in this area continues to erode, as it has in the past few years, the ability to conduct missions in the future may be dangerously compromised. It is important that NASA

- establish *adequate* funding for R&A,
- *protect* these funds from development demands, and
- regularly *review* the funding, and augment it if necessary, in order to maintain the basic research capability.

The recent NASA Space and Earth Science Advisory Committee report on *Research & Analysis in the Space and Earth Sciences* (July 1984) addressed the role and health of a continuing Research and Analysis Program in NASA and concluded that inadequate funding is the most pressing problem. We concur.

Facility Management and Operation

In several areas of space science, we can foresee the need for long-lived, multi-instrumented space facilities. It is therefore important that we now begin to consider how these facilities will be managed and operated. Questions such as management approach (principal investigators, guest observers, science institutes), on-orbit maintenance requirements, and frequency of instrument change-out will require careful study if we wish to make such facilities available to a large segment of the scientific community and to control costs so as to ensure that they are affordable.

Computer Facilities and Modeling

Modern research in solar and space physics involves an interaction between experiment and theory that is essential to continued progress. In addition, the need for employing a variety of diverse data sets to address certain problems, the large volume of data expected from some programs, the special processing requirements for certain types of data (e.g., imaging), and the need for large, multidimensional modeling studies will require more emphasis on the availability of large computing facilities and of special-purpose facilities (i.e., array processors) for general use by the scientific community. NASA should take the lead in making such facilities available not only because the agency is responsible for generating, analyzing, and interpreting much of this data, but also because NASA should be at the forefront of technological advances in space physics and should be supporting technological innovation in the use of large computers.

Space Station

In this report we have described several areas where Spacelab instruments would evolve toward use on the Space Station. Here we describe a possible scenario of how solar instruments (ASO and STO), for example, could do this. At present, it is possible only to take a preliminary look at the accommodation of science instruments on the Space Station. This is because we are only at a requirement-gathering stage of the Space Station program. There will be a period of iterative matching of science requirements with engineering design that will take place over the next 2 years. In this discussion we will only sketch some of the requirements and raise some issues that will need to be dealt with in the Space Station accommodations studies.

• *Manned Involvement*. Scientific involvement will be required in the acquisition of data and operation of the instruments of ASO or STO. Examples include control of pointing of SOT or other telescopes at different solar features of interest, and adjustment of the instrument modes to match the study of the specific solar phenomenon in progress. Also, the initiation of an active experiment such as a chemical release or an electron beam injection and the tracking of the subsequent cloud or diagnosis of the plasma instabilities generated would require continuous scientist interaction. The scientist involvement in the operation of ASO could be on-orbit direct, on-orbit remote, from the ground, or a combination of all of the preceding options.

• *Evolutionary Approach*. The four main ASO elements, SOT, POF, SXRT, and EUV should be ultimately on the same platform. Each element, however, will be developed individually, beginning with SOT. Each element would be flown initially as a Shuttle facility and later integrated onto a permanent platform. In our time line (Chapter 7), we show that when the third element, SXRT, is completed it can join SOT and POF, and the instrument collection then becomes known as ASO.

This evolutionary approach should also be used for STO. The active experiment elements of STO should be set up with close manned involvement in the early experiments. Direct attachment to the manned station would permit early studies of the operation of the equipment, i.e., beam injection at various current levels and spacecraft neutralization, wave injection coupling to the ionospheric plasma, and methods of tracking chemical releases and dealing with free-flying multiprobe and recoverable subsatellites. Basic plasma studies could be conducted in the 28° inclination orbit and the equipment operation techniques confirmed. Following this period, the active experiment package should be transferred to the 90° inclination orbit and operated with the scientist involved from the manned station or on the ground.

• *Orbital Mode*. ASO and STO will likely utilize both 90° and 28° platforms—atmospheric experiments on both, solar telescopes (ASO) on either with a slight preference for 90°, the solar variability portion of STO on either platform, and the active experiments on a manned station or a 90° inclination platform, depending on their state of evolution.

Planetary Exploration

In light of the evolving plans to implement the recent SSEC report, our Committee reviewed the future role of research in aeronomy and plasma physics in NASA's planetary program. Such research is an integral part of the planetary program and accordingly appropriate resources and portions of experiment payloads are to be allocated for such investigations. However, a trend is developing whereby aeronomy and plasma physics objectives appear to be relegated to low priorities in planned missions and little, if any, spacecraft resources are being allocated for their implementation.

We feel that the manner in which the recommendations of the SSEC report are being implemented overlooks the essential contributions made by aeronomy and plasma physics to our understanding of planetary environments and planetary evolution. Further, investigations of planetary environments have in the past and will certainly continue to result in important contributions to studies of the Earth's environment. Finally, the astrophysical implications of planetary exploration will rest in an important way on the study of plasmas.

We recommend that NASA continue its past policy of planning an appropriate mix of special purpose missions and/or missions of more general objectives with sufficient allocation of resources to permit broad investigations that include aeronomy and plasma physics. We also suggest that resources within the planetary R&A budget continue to be devoted to developing investigations in aeronomy and plasma physics for future planetary programs.

11 ORGANIZATIONAL STRUCTURE

A major intellectual thread linking several recent NAS/NRC advisory committee reports has been the essential unity of the disciplines comprising solar and space physics. The study, *Space Plasma Physics* (Colgate report), requested of the Space Science Board by NASA, attested to the scientific importance and intrinsic merit of the disciplines of space plasma physics and solar physics. The study committee, which was composed primarily of laboratory plasma physicists and astrophysicists working in areas *outside* the disciplines examined, concluded that the research in solar and space physics is also important because it contributes to significant developments in other areas of science. This conclusion was recently reiterated by the Physics Survey Committee.

Using the Colgate report as a basis, the SSB Committee on Solar and Space Physics developed the scientific strategy for future space research in the field (Kennel report). This strategy is based on a high degree of coherence among the disciplines of solar and space physics. In addition, a Geophysics Research Board study (Friedman-Intriligator report) emphasized the unity of solar-terrestrial physics and recommended directions for solar-terrestrial research in the 1980s.

This unity is not realized in NASA's organizational and management structure at present. The elements of the on-going solar and space physics program are managed by several Office of Space Science and Applications (OSSA) divisions: The Astrophysics Division is responsible for the scientific direction of SOT and ISPM, as well as managing the Explorer, sounding rocket, and balloon programs; the Solar System Exploration Division is concerned with the atmospheres and magnetospheres of all solar-system objects except the Sun and Earth; the Earth Science and Applications Division manages space plasma physics and upper atmospheric research, including UARS; the Shuttle Payload Engineering Division handles Spacelab instrumentation.

Coordinated research among the disciplines that comprise solar and space physics is an essential feature of our strategy. Such coordination will not easily be achieved with management of the various pieces split among several organizations, each with its own set of goals and priorities. The program we have proposed is substantial in terms of both scientific content and cost. We believe that NASA should consider whether its present management structure is appropriate for supporting this program.

APPENDIX: *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 the linkage of one mechanism to another in comprehensive models.

These categorizations apply equally well to in situ spacecraft investigations in solar and 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 Figure A.1 we estimate the status of in situ spacecraft investigations, in Figures A.2 and A.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 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. Figure A.4 contains our perception of the 1984 status of models of several problems in solar-system space physics, selected for their illustrative value.

*This Appendix is an update of the similar section of the Kennel report.

LEVELS OF *IN SITU* SPACECRAFT INVESTIGATION

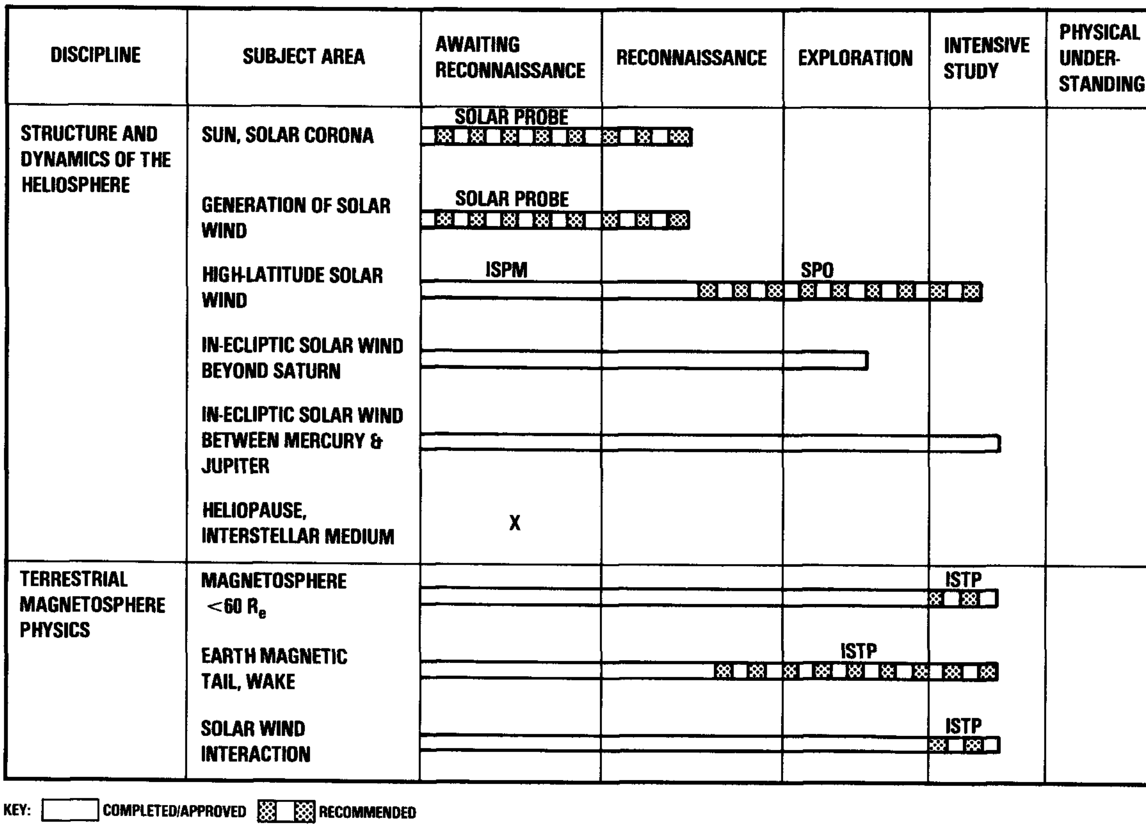


FIGURE A-1

LEVELS OF *IN SITU* SPACECRAFT INVESTIGATION (continued)

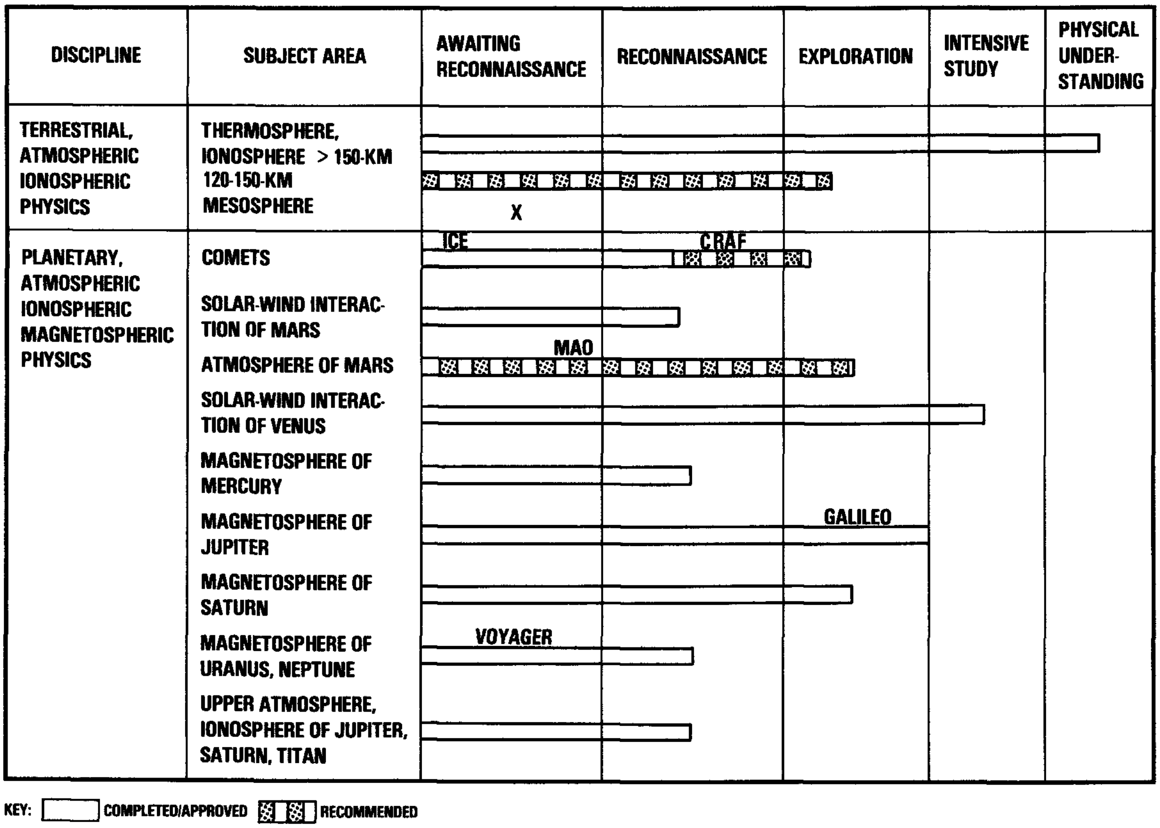


FIGURE A-1 (continued)

LEVELS OF REMOTE-SENSING INVESTIGATIONS

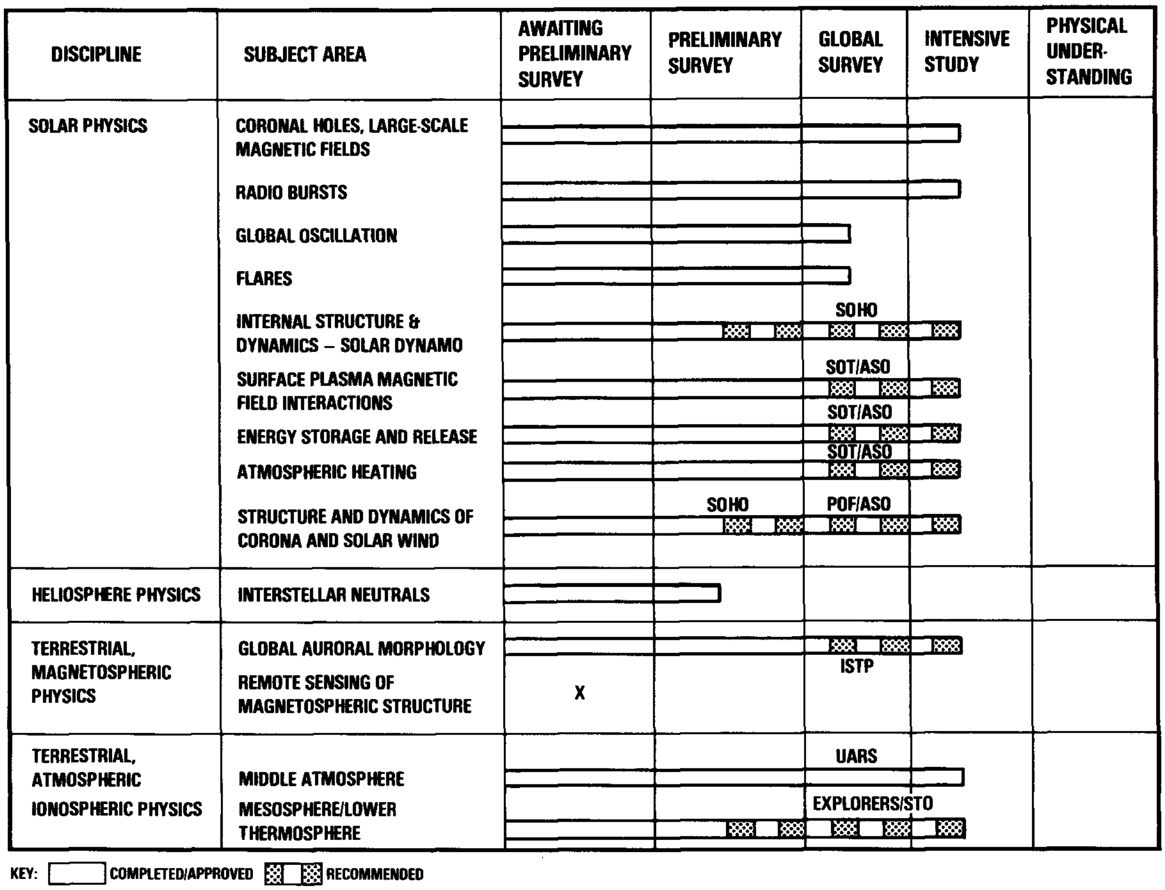


FIGURE A-2

LEVELS OF INVESTIGATION OF SELECTED ACTIVE EXPERIMENTAL TECHNIQUES

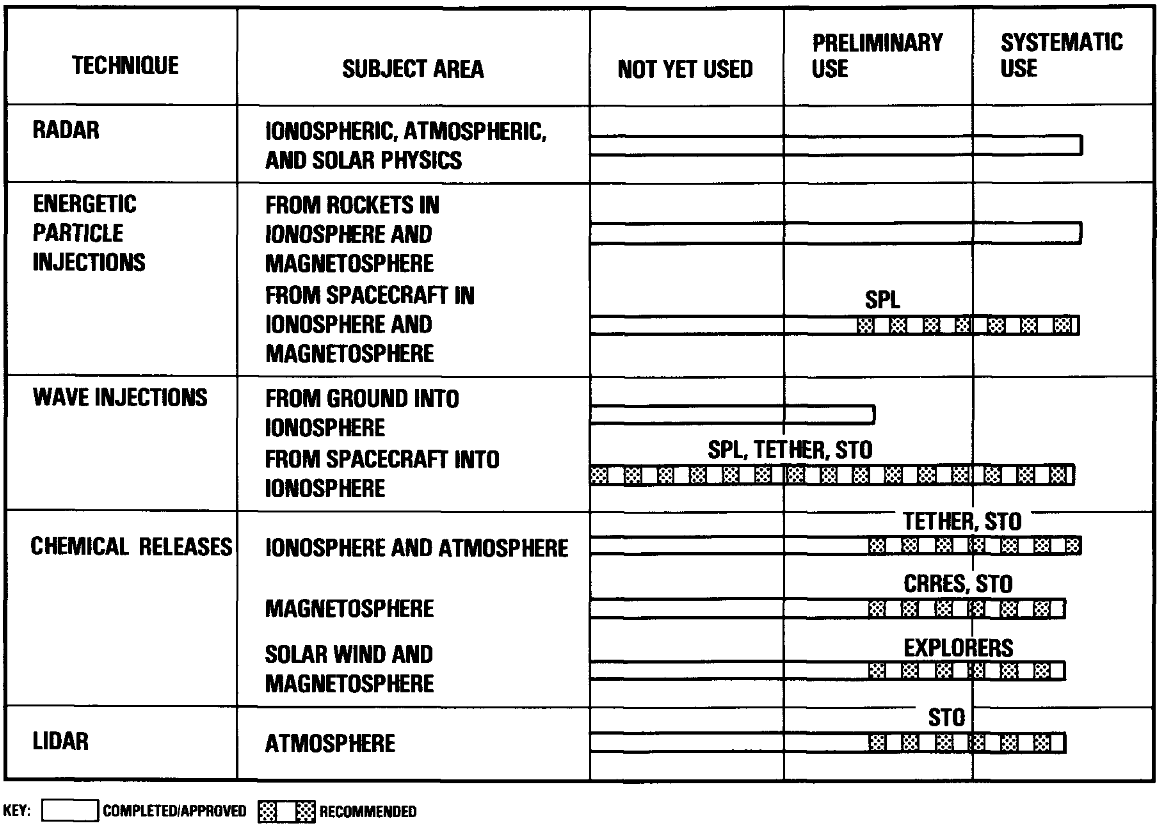


FIGURE A-3

STATUS OF PHYSICAL MODELS

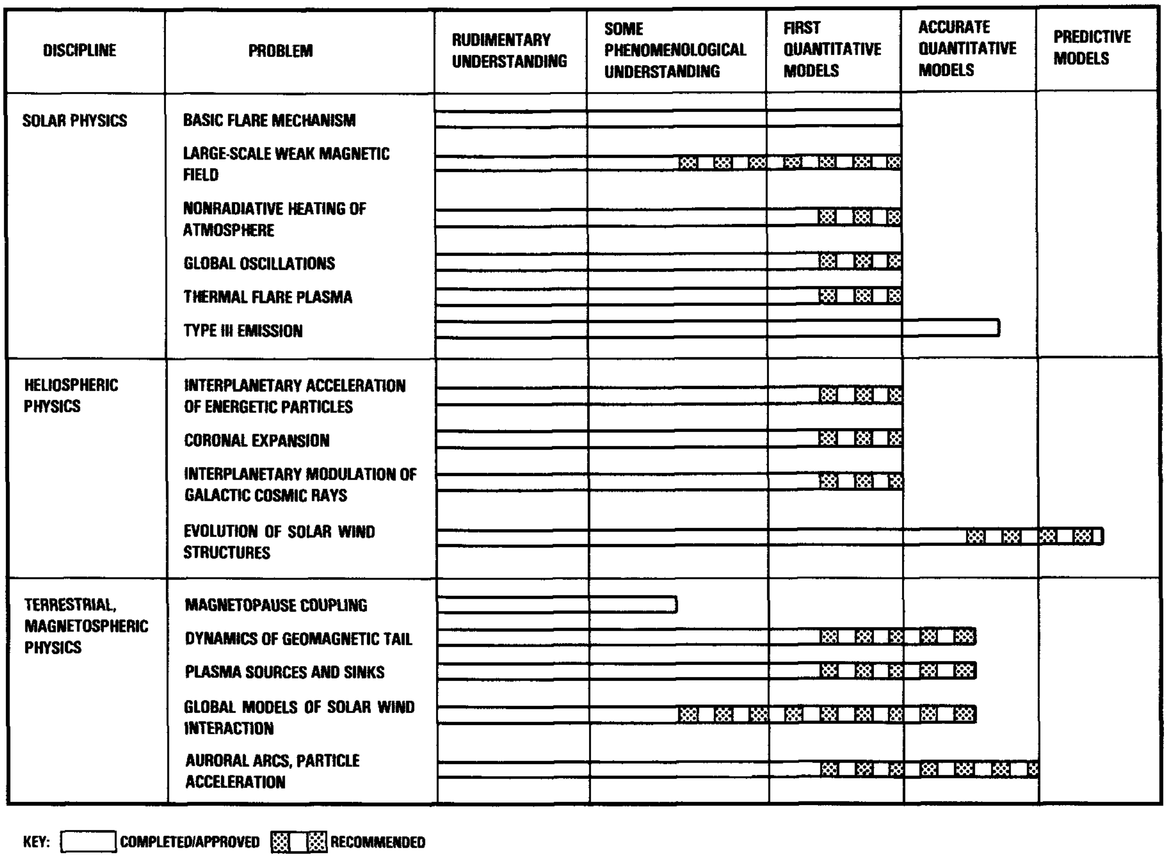


FIGURE A-4

STATUS OF PHYSICAL MODELS
(continued)

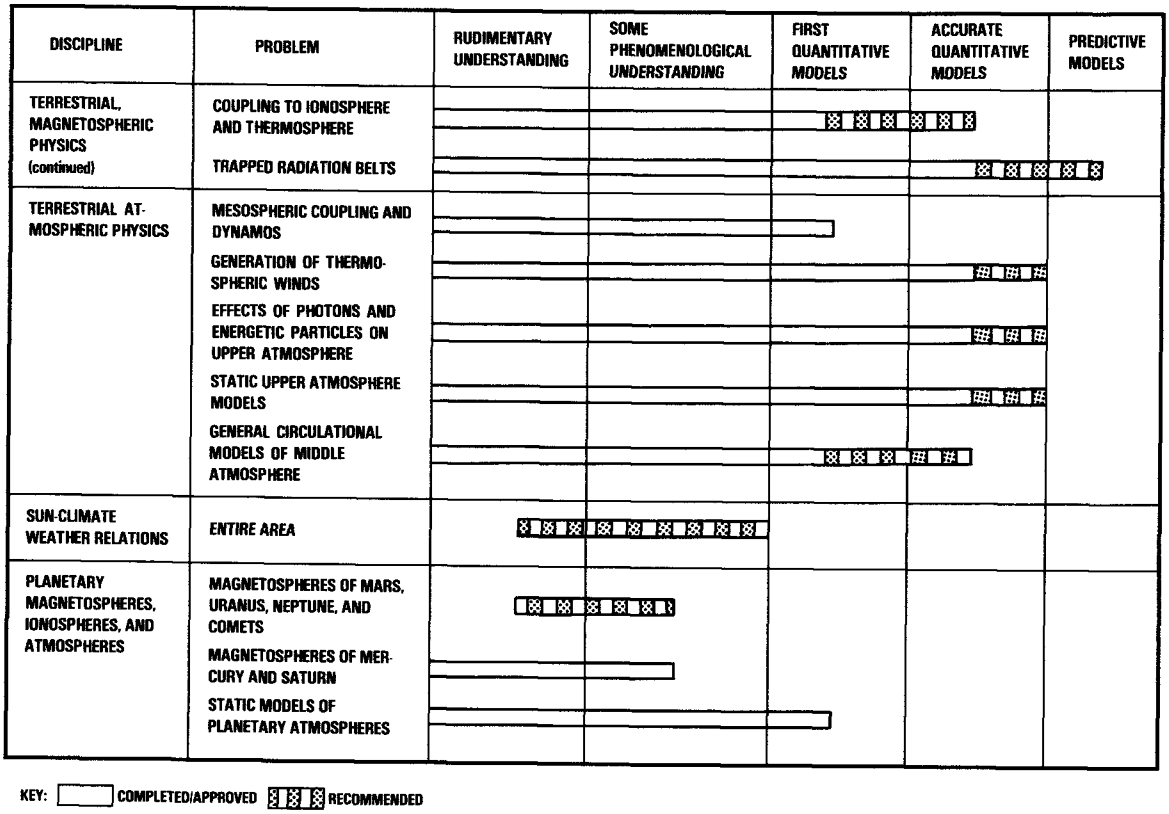


FIGURE A-4 (continued)

STATUS OF PHYSICAL MODELS
(continued)

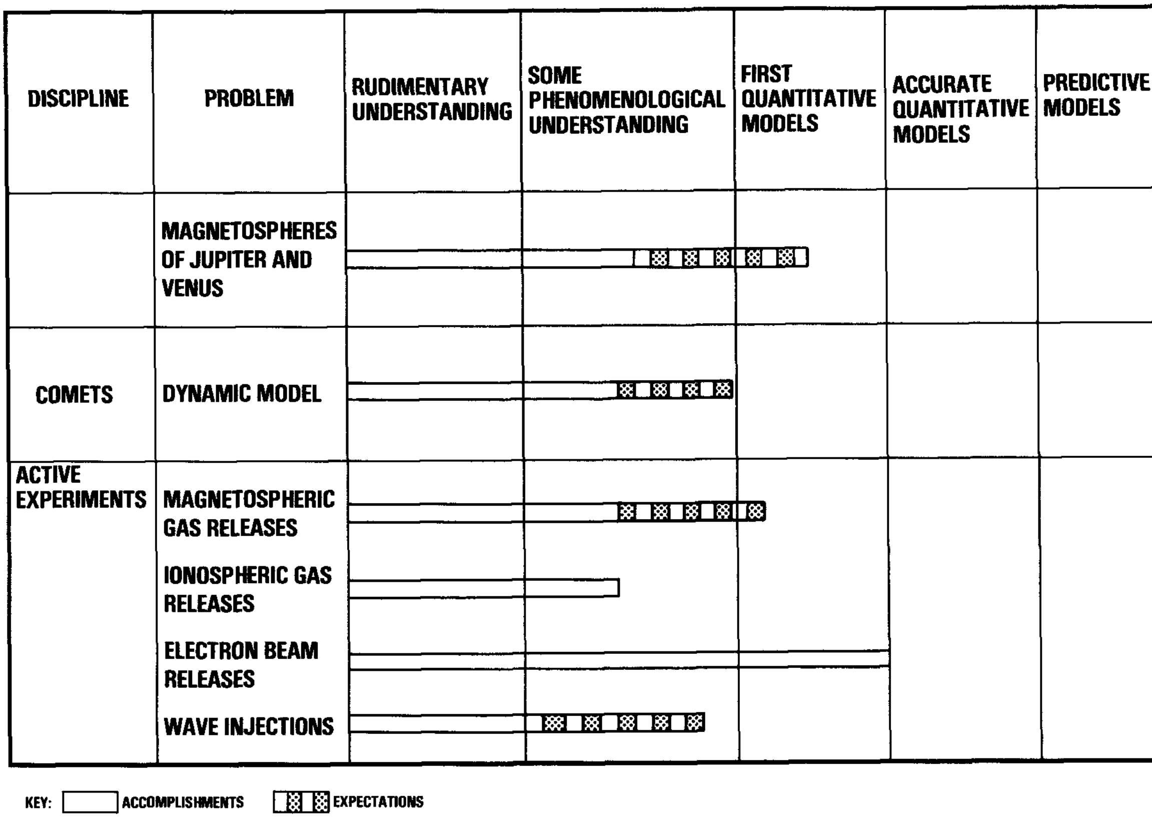


FIGURE A-4 (continued)

GLOSSARY

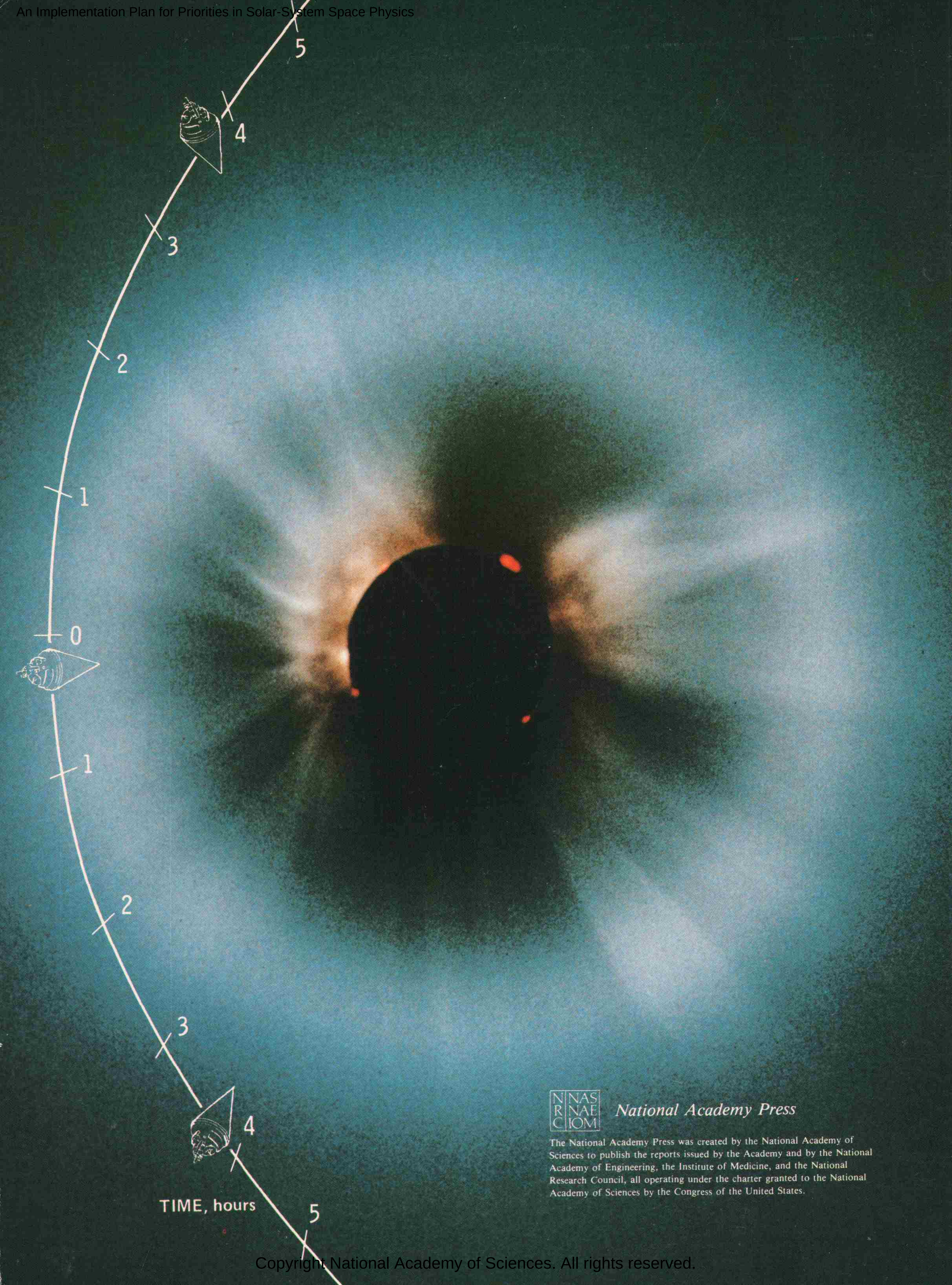
AE	Atmosphere Explorer
AMPTE	Active Magnetosphere Particle Tracer Explorer(s)
AO	Announcement of Opportunity
ASO	Advanced Solar Observatory
AU	astronomical unit
COMPLEX	Committee on Planetary and Lunar Exploration
CRRES	Combined Release and Radiation Effects Satellite
CSSP	Committee on Solar and Space Physics
DE	Dynamics Explorer
DSN	Deep Space Network
EOM	Environmental Observation Mission
ESA	European Space Agency
EUV	extreme ultraviolet
EUVT	EUV telescope
GGS	Global Geospace Study
HEAO	High Energy Astronomical Observatory
ICE	International Comet Explorer
IMP	Interplanetary Monitoring Platform
ISAS	Institute of Space and Astronautical Science, Japanese
ISEE	International Sun-Earth Explorer
ISPM	International Solar Polar Mission
ISTP	International Solar-Terrestrial Physics (program)
LEO	lower-Earth-orbit
MELTER	Mesosphere-Lower Thermosphere Explorer
MHD	magnetohydrodynamic
MO&DA	mission operations and data analysis
OMS	Orbital Maneuvering Subsystem
OSO	Orbiting Solar Observatory
OSSA	Office of Space Science and Applications
PI	principal investigator
POCC	Payload Operations Control Center
POF	Pinhole Occulter Facility
R&A	research and analysis
RPDP	Recoverable Plasma Diagnostics Package
SL	Spacelab
SME	Solar Mesosphere Explorer
SMM	Solar Maximum Mission
SOT	Solar Optical Telescope
SPAN	Space Physics Analysis Network
SPL	Space Plasma Lab
SPO	Solar Polar Orbiter
STO	Solar-Terrestrial Observatory
STTP	Solar-Terrestrial Theory Program
SXRT	soft x-ray telescope
TDRSS	Tracking and Data Relay Satellite System
TSS	Tethered Satellite System
UARS	Upper Atmospheric Research Satellite
XUVT	X-ray/Ultraviolet Telescope

Front Cover

A giant ejection of matter from the sun (blue color) as observed by the Solar Maximum Mission. Each eruption ejects about one billion tons of matter into interplanetary space. These clouds of matter travel at speeds of about three million kilometers per hour and cause global magnetic storms on Earth that produce intense auroral displays over the poles. A typical aurora viewed from the Dynamics Explorer satellite is shown in the larger inset to the left. Up to one hundred billion watts is deposited in the upper atmosphere during such displays. The solar atmosphere is so hot (over a million degrees) that it blows away from the sun as a steady wind at about a million kilometers per hour past all the known planets. The presence of this wind was originally inferred from comet tails, which always point away from the sun. The lower inset shows the first man-made comet, formed recently by a release of barium from one of the Active Magnetosphere Particle Tracer Explorers spacecraft.

Back Cover

The trajectory of Solar Probe superimposed on a picture of the sun taken during an eclipse. The pearly-white streamers are shaped by the sun's magnetic field and the solar wind and, in some eclipse pictures, can be seen to distances of over 7 million kilometers from the sun. The red prominences visible over the moon's shadow are cool gas condensations suspended in the corona, which is one hundred times as hot. The Solar Probe spacecraft would explore the sun's vicinity for the first time and approach to within about 2 million kilometers of the solar "surface." The time marks on the trajectory show that the near-sun traversal would last for 10 hours, with the spacecraft traveling at a speed of some 300 kilometers per second (over a million kilometers per hour) at closest approach. The probe would intersect many of the closed and open magnetic field structures, as is evident in the picture. The total flight time could be as short as 2.7 years, depending on available propulsion systems.



NAS NRC NAE IOM National Academy Press

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