An International Discussion on Research in Solar and Space Physics

Committee on Solar and Space Physics, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council and the European Science Foundation

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An International Discussion on Research in Solar and Space Physics

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

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The idea of a joint U.S./European Workshop on Space Physics with a balanced participation from both sides of the Atlantic was raised in the Space Science Committee of the European Science Foundation as early as 1980. Later the title was changed slightly to include also solar and heliospheric physics, earth and planetary magnetospheric physics, atmospheric ionospheric interaction, and solar-terrestrial relations.

The Workshop report has been reviewed according to the procedures of the ESF Space Science Committee. The report was approved by the ESF Executive Council in March 1984.

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PREFACE

After 23 years of space research, the goals and objectives of modern space science have evolved to the point where international cooperation is a requisite for mounting major new efforts. It is therefore important that there be opportunities for the scientific communities to meet together in organized ways to discuss their plans, to develop the scientific content of future programs, and to seek a more effective means of advising their respective space agencies.

The Space Science Board and Space Science Committee have been working together to provide more of these opportunities for candid exchanges. Since 1976 we have completed three such joint workshops. The one presented in this volume concerns solar and space physics--one of the oldest of the disciplines involved in space research and one that can provide interesting challenges for future cooperative efforts.

The main recommendation of the workshop, that an international program in solar and space physics be established, is at present being considered for implementation by National Aeronautics and Space Administration, European Space Agency, and Institute for Space and Aeronautical Science through the International Solar-Terrestrial Program (ISTP). We find it gratifying that the scientific communities and national space agencies have quickly and easily agreed to a common goal for the near-term future of these sciences.

The value of these joint workshops goes beyond the conclusions and recommendations that result. The opportunity to learn about each other's organizations, processes, constraints, and desires is of equal importance in fostering cooperation as the experimental programs that may result. We hope that these kinds of discussions will continue.

THOMAS M. DONAHUE, *Chairman*
Space Science Board
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1. INTRODUCTION

This report is the result of a four-day workshop convened jointly by the U.S. National Academy of Sciences/National Research Council and the European Science Foundation (ESF). Fifty scientists from thirteen nations attended, representing the U.S. Space Science Board (SSB) and the ESF's Space Science Committee (SSC), for the purpose of investigating the prospects for more effective cooperation in research in solar and space physics.

This workshop is the third in a series of SSB/SSC collaborations: the first, in 1976 at Williamsburg, Virginia, addressed international cooperation for the Space Telescope; the second, in 1978 at Spitzingsee, Germany, investigated cooperation in high-energy astrophysics.

The workshop began with presentations of a number of scientific papers* that reviewed the present status of several important areas of current research: solar temporal variations (D. Gough), solar wind and coronal structure (G. Withbroe), collisionless shocks (G. Paschman), recent advances in numerical simulation of space-plasma-physics problems (T. Birmingham), parallel electric fields (C.G. Fälthammar), and global thermosphere/ionosphere models (R. Roble). No attempt was made to review comprehensively the entire range of subjects in solar and space physics research; rather, these topics were selected as being characteristic examples of current research interests. Additional discussions during the workshop concerned (1) the status of solar and space physics as academic subjects, in order

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*These papers were published in the <u>ESA Journal</u>, Vol. 7, No. 4 (1983).

to investigate the potential for the future of these research areas in terms of the training of new scientists; (2) the future plans and programs of National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and several European countries, in order to assess the potential for cooperation in expected research opportunities and to understand mutually the processes by which such opportunities are created and the role of the respective scientific communities in these processes.

The last day of the full workshop was devoted to discussing U.S./European cooperation in terms of past successes and problems as well as prospects for future efforts on individual experiments, space projects, and scientific programs (including planning and data exchange). Much of the discussion concerned the differences between the U.S. and European systems in the planning of space programs, initiating missions, and selecting and developing experiments. Although these differences have sometimes posed an impediment to international cooperation, the conferees concluded that effective cooperation has not only occurred at working levels but also is required for many future programs.

The Summary and Recommendations were approved by all participants at the end of the third day. A small group of participants remained for a fourth day to draft the report of the workshop. The draft was subsequently reviewed and approved by all participants.

The major result of the workshop was the recommendation that an international solar and space physics program should be established and that it should be constructed from currently planned missions by ESA and NASA.

2. SCIENTIFIC PROBLEMS AND INTERDISCIPLINARY ASPECTS OF SOLAR AND SPACE PHYSICS

2.1 INTRODUCTION

Solar and space physics includes the study of fundamental physical processes that are important in advancing our understanding in several areas of research: plasma physics, atmospheric and ionospheric physics, magnetospheric physics, solar and heliospheric physics, astrophysics, and solar-terrestrial relations.

The scientific method employed in solar and space physics is different from that employed in the laboratory sciences. In the laboratory, controlled experiments can be performed for comparison with theory. Such controlled experiments are only occasionally possible in solar and space physics; rather, mathematical models of solar and space physics systems are constructed and compared with

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This chapter was prepared by a small group of participants after the main part of the meeting. The subject matter was not discussed in detail during the conference. The participants believed, however, that the report should reflect the broad range of scientific interests of solar and space physics and its importance to other areas of scientific research.

This chapter is only a summary of the scientific status of the field. More extensive descriptions of the status and future goals can be found in Solar-System Space Physics in the 1980's: A Research Strategy (NAS, 1980). Other recent reports of interest include Space Plasma Physics: The Study of Solar-System Plasmas (NAS, 1978); Solar-Terrestrial Research for the 1980's (NAS, 1980); Space Science in Europe (ESF, 1979); Planetary Science in Europe (ESF, 1982).

observations of these systems. As our understanding advances, the models become increasingly comprehensive, which, in turn, leads to the requirement for more comprehensive observational programs.

There has been rapid development of the field of solar and space physics since the start of the Space Age. As a result of research in space, our understanding has increased dramatically of phenomena such as collisionless shocks; the convection of plasma within magnetospheres; and the interaction of plasmas of widely different characteristics at the magnetopause, at the plasmapause, and in the transition region between the hot magnetospheric and cold ionospheric plasmas in the Earth's magnetosphere. The ionosphere has been found to play a much more active role as a supplier of plasma to the magnetosphere than believed only a few years ago. Ionospheric O^+ ions frequently are the completely dominating constituents in most of the magnetosphere during magnetic storms. Reconnection has been identified in observational data from the magnetopause.

The detailed processes involved in creating the electrodynamical generators for voltages and currents within the magnetosphere have recently become subjects of experimental study. New investigations of physical interactions involving plasma and dust and plasma and planetary satellites around the outer planets have demonstrated processes of basic importance for the understanding of plasma physics in space as well as of the development of the solar system.

Nevertheless, much remains to be understood. The observations of solar variability over a wide spectrum of frequencies must be interpreted in terms of basic solar structure. The observations of collisionless shocks have not yet been completely interpreted in terms of basic processes. The details of the entrance of solar-wind plasma through the magnetopause into the boundary layers of the magnetosphere remains to be identified. The mechanisms responsible for the large-scale extraction of ionospheric plasma into the magnetosphere are only partly known. The basic processes giving rise to the dynamos in the boundary layers are far from clear. The acceleration mechanisms for auroral primaries are still a matter of controversy. The physics of plasma-dust interaction is in its infancy.

All the processes mentioned and many other basic ones can be experimentally investigated in some detail only in our solar system and, in particular, in planetary magnetospheres. As a large part of the Universe is in the plasma state and is organized by strong magnetic fields (magnetospheres), continued efforts to understand solar and space physics are of basic importance for further development of our understanding of the Universe.

2.2 PLASMA PHYSICS

Solar and space physics is an important branch of science because it addresses problems of basic physics that are particularly interesting and challenging:

- The medium of interest is far from thermodynamic equilibrium and involves nonthermal particle distributions. Electrical charges and currents and large bulk-flow velocities play important roles. Waves and unstable fluctuations exist on a variety of different time and length scales.
- Many important interactions are nonlinear. Waves on different time and length scales couple to more complicated phenomena. Collision-free dissipation due to plasma fluctuations controls energy partitioning. Collective effects also determine the topology of magnetic fields in the process of magnetic reconnection.

- Various plasma phenomena can lead to acceleration of some particles to large energies and to bulk plasma heating.
- There exist collision-free shock waves in which the dissipation is due to collective interactions between particles and fields. The interaction of single particles with collision-free shock waves is an effective particle acceleration mechanism.
- The regions of space of interest contain a great variety of plasma populations and electromagnetic fields that interact by complicated plasma processes and that cannot be understood without knowledge of the states of neighboring regions.

Some of the most difficult and challenging problems in solar and space physics occur in the interactions between diverse plasmas in different regions. These include the following:

- The transfer of energy, momentum, and plasma between the solar wind and the magnetosphere.

- The transfer of energy and momentum from the solar interior to heat the coronal plasma and drive the solar wind.
- The energy and momentum transfer between the outer magnetosphere and the upper atmosphere and ionosphere during disturbed geomagnetic periods.
- The thermal, dynamical, and chemical structures of the upper mesosphere and lower thermosphere that are driven by tidal-, planetary-, and gravity-wave disturbances propagating from the lower atmosphere and by in situ heating and mass motions due to solar radiation and magnetohydrodynamic processes.

Major efforts are required in the development of theory and models in each of these areas in order to understand the nonlinear, coupled nature of the processes and regions.

Models that describe the mutual interactions among all of these regions and processes remain to be developed.

2.3 ATMOSPHERIC AND IONOSPHERIC PHYSICS

The Earth's atmosphere is often referred to, for convenience, as being comprised of layers: the troposphere, stratosphere, and mesosphere, for example. There is, however, intimate interplay among these layers. For example, tropospheric energy fluxes are significant in forcing motions in the middle atmosphere, changes in middle-atmospheric structures can cause changes in the middle-atmosphere transmission-reflection properties so that the wave structure in the troposphere is altered, composition coupling between regions occurs through troposphere-stratosphere exchange and through downward motions from thermospheric source regions (e.g., auroral NO), radiation coupling occurs through changes in the middle-atmosphere distribution of constituents that modulate solar and infrared radiation reaching the troposphere, and changes in radiatively active constituents in the troposphere can alter the dynamic forcing of the upper-atmospheric layers.

• Particle Input and Composition of the Middle Atmosphere

It is well established that nitric oxide (NO) production in the lower thermosphere is greatly enhanced during times of increased solar EUV radiation (associated with high levels of solar activity) and energetic particle inputs (associated with enhanced solar activity and the resulting strong magnetospheric disturbances). Since NO is an effective catalytic agent for stratospheric ozone destruction, it is important to know how much of this enhanced thermospheric NO reaches the stratosphere. Although models indicate that significant amounts of NO can be transported downward from the thermosphere at high latitudes during the polar night, detailed observations are essential in order to confirm the linkage and to provide a quantative assessment of the effects of particle input to the winter polar region on global stratospheric chemistry.

- Radiation-Chemical-Dynamical Interactions in the Middle Atmosphere

Ozone heating is important to the dynamics of the middle atmosphere. The resulting winds transport several minor constituents, leading to altered distributions from those expected from photochemical considerations alone. Transported species include ozone as well as the constituents that control ozone destruction. The quantitative evaluation of the interaction among radiative, chemical, and dynamic processes in the middle atmosphere requires a coordinated observation and modeling program.

- Solar Variability and Weather

The sun provides the energy that controls the energetics and dynamics of the atmosphere. Variations in this solar-energy input, therefore, are important factors in determining weather and climate. For example, the relationship between the major ice ages and the changes in Earth's orbital parameters (Milankovitch mechanism) illustrates the impact of changes in solar insolation. At present, the influence of solar perturbations on atmospheric processes is not known sufficiently to address questions of possible resulting changes in weather and climate. We need to understand the physical and chemical processes in the middle and upper atmosphere that couple solar variations to atmospheric changes.

- Global Electric Circuit

Although the existence of a global electric circuit has been known for many years, we still do not understand the basic processes that drive and control the behavior of the system. In the classical picture, global thunderstorm activity generates and maintains a potential difference of several hundred thousand volts between the highly conducting ionosphere and the surface of the Earth. In the fair weather dissipative portion of the circuit, this potential difference drives a vertical current downward from the ionosphere to the ground. In recent models, the ionosphere is assumed to be an equipotential surface. Nevertheless, it is clear that magnetospheric and atmospheric dynamo effects do influence the circuit in important ways.

- Ionospheric-Magnetosphere Interactions

During the last decade direct measurements of the particle population of the magnetosphere have established that a major source of this population is the ionosphere. The increasingly more sophisticated measurements of the energy, pitch angle, and composition characteristics of magnetosphere particles leave no doubt regarding the origin of these particles. However, most of the fundamental questions concerning the mechanisms responsible for the acceleration and transport of these particles from the ionosphere remain. For example, the classical polar wind theory cannot account for the observed pitch angle and energy characteristics of these particles. Use of new theoretical models, based on wave-particle interaction processes, is beginning to make possible progress in describing the controlling mechanisms.

2.4 MAGNETOSPHERIC PHYSICS

Magnetospheric physics can be considered on three widely different scales: large and small scales in terms of fluid descriptions of the plasmas and microscales when the orbits of individual particles are treated.

Large-scale processes include the global response of the magnetosphere to the variable solar and interplanetary conditions; the transport of mass, momentum, and energy into and inside the magnetosphere; the coupling of the global circulation processes to the ionosphere; the maintenance and variability of global electric current systems.

Small-scale spatial structures of the order of a few to several tens of ion gyroradii form in many plasma interactions found in the magnetosphere/solar-wind system. Vortices and eddies form in the turbulent regions of the outer cusps and adjacent boundary layers. Surface waves modulate the boundary layers and excite oscillations of internal flux tubes. The field-aligned electric currents as well as the sheet current in the tail are subject to filamentation processes.

The cross-tail electric current sheet plays a key role for the magnetospheric substorm process, which has been suggested to have counterparts in, for example, solar flares. Magnetic-field-aligned electric currents carry energy from the external energy source to the Earth's ionosphere, and plasma physical phenomena driven by these currents are responsible for the enerigization of auroral primary particles.

On the microscales we find a large variety of wave-particle interactions and instabilities: a host of plasma and radio waves, non-Maxwellian particle distributions, and preferential heating of certain ionic constituents. The anomalous transport coefficients in an otherwise collisionless medium, such as anomalous resistivity, diffusivity, and viscosity, can be significant. These anomalous processes need not simply correspond to an enhancement of the effective collision rates; more organized forms of energy conversion, such as acceleration of particle beams and the formation of double layers, can exist.

The plasma processes on all spatial scales can be intimately related. For example, reconnection implies some sort of anomalous resistivity in the crucial region of the separator or X-lines. Anomalous diffusion of some type must exist at the inner scale of eddy turbulence. The decoupling of magnetospheric convection from the ionosphere in narrow sheets (auroral oval) is due to magnetic-field-aligned electric fields. The problem of how such electric fields can be sustained in a collisionless plasma is of fundamental importance. The role of the formation of small-scales structures is that they can cause local concentrations of the electric current or other quantities and, thereby, exceed the thresholds for certain microinstabilities. These microinstabilties can create new modes of particle interactions and dissipation and strongly affect the macroscopic transport properties.

Although the Earth's magnetosphere is an obvious location for in situ observations of magnetospheric plasmas, important phenomena occur in other planetary magnetospheres, such as large centrifugal forces and moon-magnetosphere interactions in Jupiter's magnetosphere and electromagnetic phenomena in Saturn's rings.

2.5 SOLAR AND HELIOSPHERIC PHYSICS

The sun is the ultimate source of energy driving the physical processes in the heliosphere, planetary magnetospheres, and planetary atmospheres. Our understanding of the physics of the solar interior, where the energy is generated, has been challenged by the finding that the solar neutrino flux is about one third that predicted. The recent development of techniques of solar "seismology" has provided a powerful tool for probing the solar interior through observations of global oscillations of the sun measured by fluctuations of the solar diameter, surface velocities, and radiative output. Application of these techniques should yield critical information about the interior structure of the sun, its composition, and the solar dynamo.

A fundamental property of the sun is its magnetic field. The generation of solar magnetic fields in the interior, transport of these fields to the surface, and their subsequent interaction with the solar atmosphere drive the solar activity cycle and are most likely responsible for the generation of the solar corona and solar wind. Detailed studies of transient phenomena such as flares and coronal mass-ejections can lead to a better understanding of interactions between magnetic fields and plasmas. Studies of surface manifestations of the solar magnetic field, on both large and small scales, can provide insights and empirical constraints on the solar dynamo and convection zone. High-resolution observations are required to study the fine-scale atmospheric structures where the energy dissipation and plasma heating appear to occur in the low atmosphere.

Deep in the solar atmosphere, the plasma heating and flow of mass appear to be intimately related to the strength and configuration of the magnetic field that emerges from the solar surface in small, localized (about 1 arc sec) areas. Understanding the temporal and spatial variations of basic plasma parameters can provide critical empirical constraints on energy transport and dissapation mechanisms and mechanims for transport of mass. Although the energy transport and dissapation mechanisms in the corona (other than radiation and thermal conduction) are still controversial, existing observations appear to have ruled out acoustic waves as a mechanism. Improved observations are required to provide insights and empirical constraints on electrodynamic heating mechanisms. This is also the case for mechanisms believed responsible for solar-wind generation. Since our observational knowledge of the physical conditions in the solar-wind acceleration region is limited, we have been unable to distinguish between mechanisms for driving the solar wind thermally and those based on momentum transfer from magnetohydrodynamic waves. We need to understand how energy is carried into the corona from lower layers and carried away from the sun by the solar wind.

2.6 ASTROPHYSICS

The understanding achieved through solar and space physics research provides a framework for addressing a large variety of astrophysical phenomena. The solar system is the only laboratory where astrophysical processes can be studied in situ and can be compared with theory and detailed models.

The strong representation of the plasma state of matter in the Universe, and especially of magnetized plasma, makes the continued developments of our understanding of magnetospheric physics, in particular, a requirement for the continued improvement of our understanding of the Universe.

In particular, a concentrated effort in solar and space physics can be of value in the solution of the following outstanding astrophysical problems:

- The generation and evolution of magnetic fields in planets, stars, and galaxies and the radiative and electrodynamic coupling to their environment on small and large scales.
- The nature of unstable plasma phenomena and explosive (catastrophic) behavior in stars, stellar atmospheres, pulsars, accreting galactic x-ray sources, active galactic nuclei, radiogalaxies, and quasars.
- The generation of radio waves by nonthermal particle distributions in planetary magnetospheres and in astrophysical sources.

Some results from space-physics research that are likely to affect future astrophysical research strongly are the following:

- Space appears to have a cellular structure, i.e., plasma systems of widely different characteristics are separated from each other by narrow boundary layers (the existence of which is difficult to establish except by in situ measurements).

- Contrary to gravitation, which tends to produce spherical structures, the electromagnetic interactions in space tend to produce filamentary structures or thin surfaces (carrying currents).

The main importance of solar and space physics, however, lies in the unique opportunities that the field offers to improve understanding of basic physical phenomena that is difficult to achieve in other ways.

3. SOLAR AND SPACE PHYSICS
IN THE ACADEMIC ENVIRONMENT

3.1 *INTRODUCTION*

Solar and space physics has undergone a remarkable expansion and evolution in the last 20 years. The field barely existed before that time, and yet now it is in a transition from a largely observational and discovery phase into a mature science, consisting of a balanced combination of theory, observation, laboratory and computer simulations, modeling, and data analysis. Many processes observed in the solar system are also observed in laboratory and astrophysical plasmas, e.g., magnetic reconnection. Thus, space physics has an important role to play in advancing plasma physics in general. Nonetheless, it is fair to say that the field's academic stature has not advanced concomitantly with its scientific contributions. Like any other discipline there is a need for highly trained scientists, a healthy balance between teaching and timely research opportunities, and the physical resources to execute the scientific programs. This chapter discusses the status of the field with regard to these elements in both Europe and the United States.

3.2 ACADEMIC STATUS

United States

Following a rapid upsurge in the 1960s and a decline in the 1970s, the funding for space science now appears quasi-stable. These rapid changes have promoted research in the field but have hindered its academic growth. Approximately 60 PhD's graduate every year with major concentrations in solar, magnetosphere, and upper-atmosphere physics. By technique, they are distributed as follows: theory, 45 percent; experimental, 33 percent; and data analysis, 22 percent. Much of the theory involves plasma physics, with rapid growth in computer modeling and simulations. Graduates have no difficulty in finding positions in industry, and, if anything, there is a surfeit of postdoctoral positions. This may be partially due to a dearth of tenure-track assistant professorships. The education of students is deemed adequate, although a lack of textbooks is noted. Several suggestions can be made for improving the educational opportunities and assuring adequately prepared students in the field: include space physics in undergraduate survey courses, employ undergraduates in space-physics research laboratories, and use space-physics graduate students to teach beginning physics courses. At the graduate level there appears to be a lack of opportunity to do experimental research on space, rocket, balloon, or ground-based projects of reasonable duration.

Many European students and postdoctoral assistants attend U.S. universities; for example, in 1979, fully 49 percent of the postdoctoral positions in the physical sciences were occupied by foreign-born nationals. European opportunities for U.S. citizens are probably not so numerous but are no less important to the space-science community.

Approximately one half of the space plasma research community (magnetospheric and ionospheric) was affiliated with universities in 1982. Only a third of the solar physicists were so affiliated in 1980, demonstrating the academic weakness of that field. These relatively low percentages in academia are compounded by the fact that less than one half of these university-affiliated researchers actually have full faculty positions. This points to an underrepresentation of solar and space physics within universities in the United States.

Finally, we can compare the average ages of an international mixture of space physicists publishing in the Journal of Geophysical Research (mostly about the magnetosphere and ionosphere). In 1963 the average age was 35 ± 1 years and in 1983 it was 43 ± 1 years. In recent years, the average age has been increasing at an accelerating pace, which is now about 9 months per year. Much of this can be attributed to a lack of opportunity in the academic environment for young solar and space physicists.

Europe

It is not an easy task to obtain comparable statistical material documenting the academic representation of solar and space physics in various Western European nations. It was only possible to compare some of the appropriate quantities, such as numbers of weekly lectures, or relative numbers of weekly lectures, or relative numbers of universities engaged in this field among a small number of nations. What emerges is not conclusive, but quite indicative.

The following results appear to be significant (at least to an order of magnitude): the ratios of courses (or lectures) offered in solar and space physics to those in general astrophysics and to those in general physics, appear to lie near 1:7 and near 1:100, respectively. In solar and space physics the ratio of solar to space physics ranges near 1:2. Space physics appears to be as frequently represented as general plasma physics. The relative number of universities offering courses in solar and space physics and astrophysics compared with those offering an education in physics is quite variable: between 30 and 80 percent offer general astronomy and astrophysics, and about one half offer solar and space physics.

The main conclusion emerging from this statistical study is that in view of the great efforts in space sciences, both by way of programs and maintenance of national laboratories, the representation of the field in the academic curriculum could be improved. The concern is not so much about the number of students from which the researchers of tomorrow can be recruited as it is about the lack of penetration of a fascinating science, one relevant to an understanding of the structure of the Universe, into the academic and general cultural life of society. Ways should be sought to give this lively field better academic visibility.

3.3 SUMMARY AND CONCLUSIONS

Solar and space physics as an academic subject displays some imbalances in numbers of students, faculty, and courses offered; its status is consistent with being a relatively young subject. As such, it is not yet fully integrated into the academic structure of departments of physics, astronomy, and atmospheric science despite the overall growth of plasma physics and the central role played by solar and space plasma research in relating laboratory research to astrophysical plasmas. The academic health of the field could be enhanced by increased course offerings at both the graduate and undergraduate level, a greater number of tenure-track faculty positions, more experimental research opportunities of short duration (i.e., space, rocket, and balloon), and better and more numerous textbooks.

4. TOWARD AN INTERNATIONAL PROGRAM IN SOLAR AND SPACE PHYSICS

4.1 INTRODUCTION

Solar and space physics matured as sciences during the past two decades. This has been the result of the many space programs that have been carried out successfully by the United States, Europe, Japan, and the Soviet Union. In many of these programs, close cooperation between U.S. and European researchers has been the rule, and coordinated experiments and projects have become the mainstay of solar and space physics programs both in the United States and Europe. Examples of this cooperation are the conduct of joint missions such as the International Sun-Earth Explorer; European investigator participation on U.S. missions such as the Orbiting Solar Observatory, Interplanetary Monitoring Platform, and Solar Maximum Mission; and U.S. investigator participation on European missions such as UK-5 and Helios. This close cooperation between the two scientific communities is further reflected in a great many instruments having been successfully developed with contributions from both sides of the Atlantic. This applies at the level of sounding rockets, small satellites, and major projects. Several missions that are in preparation at this time also exhibit this mode of close collaboration (International Solar Polar Mission, Active Magnetosphere Particle Tracer Experiment, Viking).

Several new missions in solar and space physics are in the planning stage or have been proposed at the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). These missions are complementary and address rather advanced scientific problems in solar and space physics, concerning both the sun-Earth system as well as specific physical processes on the sun or in the Earth's plasma environment. The nature of these proposed programs, together with the mutual scientific objectives of the United States and European research communities, should lead naturally to the development of a strong international program in solar and space physics. Continued coordination and cooperation of the two agencies, NASA and ESA, will be required for the implementation of such a program.

4.2 IDENTIFICATION OF POTENTIAL PROGRAM ELEMENTS

From the discussions in Chapter 2, we can identify the following general research elements as forming a strong scientific framework for a potential international program in solar and space physics: the study of the sun, the study of the solar-terrestrial system, and the study of large- and small-scale solar-system plasma structures. In the following, we identify NASA and ESA program elements that are responsive directly to these research elements.

Understanding the evolution of the sun and its energy output will require studies both to probe the solar interior and to observe surface and coronal processes. Understanding how the energy released from the sun affects the terrestrial environment will require observations of the solar-terrestrial system ranging from how energy is released by the sun, how it propagates to and through the Earth environment, to how it is deposited in the Earth's atmosphere. Understanding how energy, mass, and momentum are transported across the many plasma boundaries in the path from the solar interior to the Earth's atmosphere will require studies of large- and small-scale plasma structures and their interactions throughout the sun-Earth system.

Table 4.1 shows a compilation of planned satellite programs that have been proposed by the U.S. and European scientific communities in the field of solar and space physics. An international program based on these planned programs will be directly responsive to the science elements discussed above and will be a natural extension of past and existing collaborative efforts.

Table 4.1 also shows the science elements that are the objectives of each of the identified programs, in order to demonstrate how these programs contribute to the basic science elements discussed above, namely, studies of (1) the sun, (2) the solar-terrestrial system and (3) space plasma physics.

TABLE 4.1 Candidates for Cooperative Programs in Solar and Space Physics--NASA and ESA

Organization	Program[a]	Launch	Primary Science Elements[b]	Primary Observational Objective
NASA	UARS	1989-1990	2	Upper-atmosphere observations
NASA	OPEN	1989	2,3	Interplanetary and magnetospheric observations
ESA	SOHO	1992-1993	1,2	Solar observations
ESA,	CLUSTER	1992-1993	3,2	Plasma turbulence observations
NASA, various national institutions	Explorers, national satellite projects	Continuing	1,2,3	Localized physics problems in solar and space physics
International associations (e.g., EISCAT); national institutions and NASA	Ground-based	Continuing	1,2,3	Currents, plasma structures, auroral displays, solar observations
International associations (e.g., EISCAT); national institutions and NASA	Theory and modeling	Continuing	1,2,3	Use of data to guide theory and models; use of models and theory to predict observations

[a] Space programs described more fully in text.
[b] 1, solar studies; 2, solar-terrestrial system studies; 3, space plasma physics.

The major scientific goal of the Upper Atmosphere Research Satellite (UARS) is to study the energetics, composition, and dynamics of the Earth's upper atmosphere in order to provide a key element in understanding the dynamics of the solar-terrestrial system by measuring the atmosphere's response to variations in the energy input from both the sun and the magnetosphere.

The goal of the Origins of Plasmas in the Earth's Neighborhood (OPEN) program is to measure the energy, mass, and momentum flow from the solar wind throughout the magnetosphere and to ultimate deposition in the ionosphere and the upper atmosphere. OPEN consists of four satellite laboratories placed to make observations in the following key regions:

- IPL (Interplanetary Physics Laboratory) or Wind[*]--solar-wind source (launch in 1989);
- PPL (Polar Plasma Laboratory) or Polar[*]--ionosphere source (launch in 1990);
- EML (Equatorial Magnetosphere Laboratory) or Equator--ring current storage (launch in 1990);
- GTL[†] (Geomagnetic Tail Laboratory) or Tail[*]--deep tail storage (launch in 1991).

The primary science goals of the Solar and Heliospheric Observatory (SOHO) are to study the outer layers of the sun (chromosphere, transition region, and corona), to probe the solar interior by measuring solar surface velocity and luminosity variations, and to provide measurements of the solar wind. Thus, SOHO is a key element in a solar and space physics program that will perform direct measurements of the sun and its dynamics as well as provide the solar-related observations required for solar-terrestrial system studies. The solar-wind observations in conjunction with IPL measurements can be used to study heliospheric plasma phenomena.

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[*] For an international program in solar and space physics it is convenient to rename each of the spacecraft in terms of the region of space that they will investigate.

[†] Discussions between the United States and Japan (Institute of Space and Astronautical Science) indicate the strong likelihood that the Japanese OPEN-J spacecraft can fulfill the deep tail objectives of the OPEN/GTL. It has, therefore, been proposed that Japan build the OPEN-J/GTL spacecraft and participate as a full partner with the United States in the OPEN program.

The main scientific objective of the CLUSTER program is to study plasma turbulence and small-scale plasma phenomena. Four satellites will be employed to provide a three-dimensional set of observations. The plasma phenomena of various regions of the magnetosphere will be studied: for example, the magnetopause will provide an environment for the study of plasma boundary phenomena and reconnection processes, the dayside cusp region will provide an environment to study plasma turbulence, and the bow shock is an environment for studies of collisionless shocks in plasmas. Thus, CLUSTER provides a key element of our scientific framework by performing the basic studies of small-scale plasma structures and plasma turbulence. These measurements, when combined with the OPEN and SOHO observations, will provide important contributions to studies of the solar-terrestrial system.

The smaller, national or bilateral satellite projects and the NASA Explorer program would greatly enhance the international program in solar and space physics. These missions are generally either dedicated to studies of specific solar-terrestrial regions (e.g., the Viking project) or concentrate on specific physics studies (e.g., the USA-Italy Tethered Satellite System or the proposed USA Plasma Turbulence Explorer). Such studies naturally fit into, and contribute to, an overall solar and space physics program.

A final key observational element is the ground-based, rocket, and balloon programs conducted in solar and space physics in both the United States and Europe. In most cases, these programs provide observations that are not possible by any other methods or provide an especially efficient method of obtaining difficult observations. They also provide a means of developing and testing new experiments. The ground-based, rocket, and balloon programs contribute significantly to all three science elements listed above.

The theory and modeling programs in solar and space physics are required to guide the observational programs, to unite the variety of observations necessary to test quantitatively theoretical understanding of the physics involved, and to aid in identifying new directions that must be taken to improve understanding. The theory and modeling programs contribute directly to all three science elements being considered.

It should be emphasized that the different spacecraft elements in Table 4.1 can stand by themselves, i.e., the disappearance of one element from the list does not eliminate the major scientific interest of the others. On the other hand, there are generally quite important scientific benefits of combining simultaneous measurements in many points in the extremely complex physical system that the solar wind-Earth's magnetosphere-upper atmosphere constitute. Important additional scientific values can therefore generally be achieved by suitable coordination of the timing and instrumentation of various spacecraft in Table 4.1, and others. One example of such an important coordination would be if the Wind (IPL) satellite of the OPEN program could be launched in time (1989) to support the International Solar Polar Mission mission during its passage over the polar regions of the sun.

In summary, the NASA and ESA program elements shown in Table 4.1 and discussed above establish a strong foundation for an international program in solar and space physics. It is important that the implementation of the program be coordinated at the scientific level to ensure the complimentarity of the elements, to avoid duplication of effort, and to ensure that each individual element contributes in the best possible way to an overall program in solar and space physics.

4.3 DATA EXCHANGE AND AVAILABILITY

Progress in the field of solar and space physics requires the combination and comparison of data from many sources: separate instruments on single spacecraft, all the components in a multispacecraft program, and data from ground-based instruments. These data must be available to investigators for an extended time in order that the scientific problems under investigation can be systematically solved. Various data-exchange and coordination schemes have already been tried (e.g., S^3, Atmosphere Explorer, International Sun-Earth Explorer, Dynamics Explorer, Coordinated Data Analysis Workshop, Solar Maximum Mission) and extensions of these schemes are being developed (e.g., Active Magnetosphere Particle Tracer Experiment, Origin of Plasmas in the Earth's Neighborhood, Upper Atmosphere Research Satellite). The technology required to deal with mass data storage and transportation now exists. What remains to be addressed are problems associated with the availability and accessibility of data. An international program in solar and space physics can provide the framework of cooperation needed to solve these problems.

5. INTERNATIONAL COOPERATION: SUCCESSES AND PROBLEMS

International cooperation was examined at several levels: intellectual exchanges, individual experiments, joint projects, and government or agency policies.

5.1 INTELLECTUAL EXCHANGES

Intellectual exchanges between the United States and Europe in the area of solar and space physics are excellent. International meetings and symposia have been valuable vehicles for the exchange of ideas between individual researchers. The frequency and productivity of visiting scientist programs is highly commendable on both sides of the Atlantic.

5.2 INDIVIDUAL EXPERIMENTS

U.S./European cooperation works extremely well at the level of individual joint experiments. The number of European co-investigators on U.S. experiments and the number of American co-investigators on European experiments have been increasing in recent years. For example, approximately 60 Europeans have been selected as co-investigators for the U.S. OPEN mission, while there are over 30 U.S. co-investigators in ESA's Giotto Mission.

5.3 JOINT PROJECTS

There have been several highly successful joint U.S./ European space missions, both with individual European nations (e.g., HELIOS) and with ESA (e.g., ISEE). A few problems have arisen, however, because of the differences in the policies and practices of the two space agencies.

One problem arises from the differences in the way projects are planned, scheduled, and funded in the United States and Europe. The ESA science program is funded at a constant level, year after year, and ESA carries out its missions in a predetermined sequence, as they can be fit within that budget. This is much the same as the method of financing U.S. Explorer missions. Large U.S. missions, however, are subject to annual budgetary scrutiny, which can lead to unilateral cancellation of agreed-upon international projects, such as the U.S. spacecraft for ISPM. The conferees agree that means should be sought to improve the security of such joint agreements. Without such security, planning of joint missions, such as probe plus carrier missions, would be nearly impossible because the withdrawal of one partner would jeopardize the entire mission.

Other problems arise from the differences in funding of the science for NASA and ESA missions. In general, NASA pays for U.S. experiments, whereas ESA does not pay for experiments flown on its spacecraft. In the latter case, scientists are funded by their individual countries. This difference has two consequences: (1) NASA has more direct control of the development of each instrument than does ESA; and, because it is financially responsible for the instrument, NASA has a strong interest in its integration into the spacecraft. It takes a while for both U.S. and European scientists to adjust to each other's system, causing problems to schedules and budgets, for example. (2) In Europe any interexperiment data exchange must be paid for by the individual experimenters involved. We suggest that steps be taken to enable European investigators to participate in the electronically accessed data catalog now evolving in the United States.

5.4 POLICY LEVEL

This is the level at which the differences and the impediments to cooperation are greatest. We mention only four items that received the most discussion at the conference:

1. U.S. scientists have developed a long-range plan for solar and space physics. The principal goals of the field have been described in several reports published by the National Academy of Sciences/National Research Council. There are few equivalent European documents. Each time ESA has the funds to start a new mission, there is an open competition among many candidate missions. The conferees agreed that because the overall scientific goals are the same, joint planning is not only still feasible but also should be encouraged in order to enable the development of complementary, cooperative, or even joint missions, rather than competing missions.

2. In recent years NASA has selected experiments before a mission is approved, whereas ESA does not solicit proposals for experiments until after mission approval. In the case of joint projects, such as ISEE or ISPM, the two agencies tried to use a similar procedure. This process could become difficult, however, for a joint mission composed of several spacecraft originally planned as independent programs.

3. In the past, European scientists could propose experiments for NASA missions, but U.S. proposals were not invited for ESA missions. Following a recommendation of the SSC of the ESF, ESA has recently reversed this position, and NASA and ESA are in the process of negotiating how to implement the inclusion of U.S. experiments on future ESA missions. The conferees applaud this development and urge the timely implementation of a mechanism to supply U.S. instruments to ESA missions without imposing the NASA way of doing business on either the experimenters or the project.

4. The method of rating and selecting experiments for ISPM generated some feelings of ill-will among scientists. The discussion at the Workshop revealed that the main problem was that before the selection a rating was done independently by the two agencies. The conferees endorse the joint selection of experiments, with any scientist being able to propose an experiment for any spacecraft in a multispacecraft mission. The conferees suggest that each partner rate or establish priorities for only the experiments from its own side before the joint selection begins.

6. SUMMARY AND RECOMMENDATIONS

- The conferees heard formal presentations on illustrative problems of frontier research in solar and space physics and discussed recent National Academy of Sciences/National Research Council reports in these areas. The conferees agree that these reports established the scientific rationale for a research program to attain important advances in these areas.
- The conferees agreed that major solar, heliospheric, magnetospheric, and upper-atmospheric flight programs currently in planning stages in the United States and Europe address many of the important scientific goals in solar and space physics.
- The conferees recommend the establishment of an international program in solar and space physics where major projects currently identified at NASA and ESA, both separate and joint, will form complementary elements. This program should include as additional elements smaller-scale payloads (both Shuttleborne and free-flying spacecraft) designed to address specific problems; appropriate ground-based, balloon, and rocket facilities; and theory and numerical simulation.
- The conferees recommend that improved means of data exchange be designed so that data from various elements of the international program are widely accessible throughout the respective scientific communities.
- The conferees' examination of solar and space physics as academic subjects revealed that educational opportunities in this subject area are limited when compared with the broad scope of research activities being conducted in both the United States and Europe. We therefore recommend a determined effort to strengthen the

teaching of this subject area in physical-science curricula.

- The conferees found the exchange of views on the respective space-science objectives and programs extremely useful and recommend that the Space Science Board and the Space Science Committee establish a mechanism whereby such dialogues can continue at periodic intervals.