NASA Conference Publication 3048

Solar-Terrestrial Science Strategy Workshop

Proceedings of a workshop held at
Stanford University
Stanford, California
September 12-16, 1988

NASA

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Peter M. Banks
STSSW Chairman

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Stanford, California

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Acronyms, Abbreviations and Project Names

ACE	Advanced Composition Explorer
Active	USSR active experiment spacecraft
AE	Atmosphere Explorer
AIM	Atmosphere-ionosphere-magnetosphere
AKR	Auroral kilometric radiation
AMPTE	Active Magnetospheric Particle Tracer Explorer
Apex	USSR active experiment spacecraft
Apollo	US manned lunar exploration program
ASO	Advanced Solar Observatory
ATLAS	Atmospheric and Terrestrial Laboratory for Application in Space
AU	Astronomical unit
CCE	Charge Composition Explorer
Challenger	Space shuttle; destroyed 28 Jan 1986
Cluster	Multiple spacecraft; element of ISTP
Cosmos	USSR spacecraft series
CRRES	Combined Release and Radiation Effects Satellite
DE	Dynamic Explorer
Echo	Early US passive communications satellite
emf	Electromotive force
EOS	Earth observing system
Equator	Element of ISTP; equatorial orbit satellite
ESA	European Space Agency
EUV	Extreme ultraviolet
EXOS-D	Japanese research spacecraft program
Gallium	Search for low energy solar neutrons with gallium detector
GFSC	Goddard Space Flight Center
GGS	Global geospace science
Geotail	Element of ISTP; geomagnetic tail exploration satellite
HEF	High energy facility
HEIC	High energy instrument cluster
HILAT	High Latitude Satellite
Hinotori	Japanese research satellite
HRTC	High resolution telescope cluster
IKI	Space Research Institute (USSR)
IMF	Interplanetary magnetic field
IMP	Interplanetary Monitoring Platform
IOC	In orbit construction
IR	Infrared
IRI	International Reference Ionosphere
ISIS	International Satellite for Ionospheric Studies
ISO	International Standards Organization
ISPM	International Solar Polar Mission
ISPM	International Solar Polar Mission, now Ulysses
ISTP	International Solar-Terrestrial Program
IUE	International Ultraviolet Explorer

Acronyms, Abbreviations and Project Names (Continued)

Janus	Concept for sun/Earth observation satellite
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LEO	Low Earth orbit
Max-91	Coordinated solar research program
MELTER	Mesosphere Lower Thermosphere Explorer
MHD	Magnetohydrodynamic
Mir	USSR space station
MIT	Massachusetts Institute of Technology
MSFC	Marshall Space Flight Center
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administrator
NRL	Naval Research Laboratory
NSTS	National Space Transportation System (also space shuttle, shuttle, STS)
OGO	Orbiting Geophysical Laboratory
OSL	Orbiting Solar Laboratory
OSSA	Office of Space Science and Applications (NASA)
P/OF	Pinhole/Occulter Facility
Polar	Element of ISTP; polar orbiting satellite
Polar Bear	Polar Beacon Experiments and Research Satellite
RMS	Remote manipulator system
San Marco	Italian research satellite program
SEPAC	Spare experiments with particle accelerators
SESAC	Space and Earth Sciences Advisory Committee
Skylab	US space station; reentered 7 Nov 1979
SL	Skylab
SMM	Solar maximum mission
SOHO	Solar and Heliospheric Observatory
Solar-A	Japanese solar research satellite
Solar Probe	US near-sun exploration program
SPAN	Space Physics Analysis Network
SS	International Space Station, Freedom
STO	Solar-Terrestrial Observatory
STSS	Solar-Terrestrial Sciences Strategy
SVO	Solar Variability Observatory
SWG	Science Working Group
SWRI	Southwest Research Institute
TSS	Tethered satellite system

Acronyms, Abbreviations and Project Names (Concluded)

UARS	Upper Atmosphere Research Satellite
UCSD	University of California, San Diego
UHF	Ultrahigh frequency
Ulysses	European solar polar mission
UV	Ultraviolet
VHF	Very high frequency
Viking	Swedith auroral region exploration satellite
VLF	Very low frequency
WISP	Waves in space plasmas
XUV	X-ray ultraviolet

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Chapter 1

Background of the Workshop

1.1 Introduction

The age of space research spans only 30 years, yet even in such a short period the progress of solar-terrestrial science can be divided into three major epochs of development. During the 1960s abundant opportunities for space flight led to rapid exploration and characterization of the Earth's outer atmosphere and ionospheric plasma envelope. The terrestrial radiation belts were detected and explained. The boundary between the terrestrial magnetic field and the interplanetary solar wind was discovered. Space observations of the ultraviolet and x-ray portions of the solar spectrum led to an appreciation of the complex processes present in the solar atmosphere. It was during this same era that the processes underlying previously postulated sun-Earth radiative and particle couplings were established with certainty. It was also a time when various satellite missions were defined and quickly developed. Late in the decade, the Apollo missions to the moon provided the opportunity for measurements of the solar wind and the interplanetary magnetic field from temporary lunar bases.

The fruits of planning and knowledge gained from the 1960s were harvested in the 1970s. Many significant atmospheric, ionospheric, magnetospheric, and solar measurements were made with balloons, rockets, and satellites. The concept of pervasive couplings between Earth's upper atmosphere, ionosphere, and magnetosphere emerged and was verified by experiments investigating some of these complex interactions. Skylab, the offspring of a more ambitious space station program, provided rapid response, high resolution images and spectra of flares and other dynamic solar processes. The 1970s also saw the development of National Space Transportation System with its space shuttle.

Solar-terrestrial science of the 1980s has progressed at a more measured pace than in the preceeding two decades. This has resulted from various influences, from: (a) the increasing costs for more complex and sophisticated payloads, (b) a slowly growing national space research budget, and (c) the increasing competition between scientific disciplines for space platforms. These factors, acting in concert, resulted in a significant reduction in the number of flight opportunities for solar-terrestrial science as compared with the earlier two epochs. Small ventures proved difficult to inaugurate, intramural competition for new flight programs became intense, and the time between major flight programs was lengthened. Nevertheless researchers created new models and computer simulations of the Earth's space environment. Noteworthy missions include the Solar Maximum Mission, the Dynamics Explorer satellites, Active Magnetospheric Particle Tracer Explorer (AMPTE) and Charge Composition Explorer (CCE), and the recently flown San Marco satellite. NASA's Theory Program also provided a new means for interpreting space data in terms of global, interactive processes.

Two shuttle-borne Spacelab missions devoted largely to solar-terrestrial science were launched before the Challenger accident in January 1986. These have demonstrated both the strengths and the weaknesses of the shuttle as a platform for scientific experiments. The Challenger accident, however, caused a succession of cancelled shuttle flights and ripple-down delays in the initiation of major, new flight programs which affected the entire solar-terrestrial research community. The long-term effects of the accident will be seen for a significant part of the next decade, and science advisory bodies to NASA have explored the situation in the important report from the Space and Earth Sciences Advisory Committee, "Crisis in Space Science."

Yet, even with this discouraging turn of events, the NASA program for near-term space flights devoted to solar-terrestrial science has developed with surprising vigor. A list of currently operating and near-term missions under development for the next 5 years is given in Table 1. From this, it appears that the needs of

Table 1. Current NASA Program in Solar-Terrestrial Science

Operating	Near Term	In Planning
Solar Processes		
SMM	Max-91	OSL
Rockets (5/year)	Solar-A	Solar Probe
	SOHO	Rockets (7/year)
	Rockets (5/year)	Space Station Attached Payloads
		Explorers (ACE)
		Small Explorers
Geospace System		
IMP	CRRES	EOS
DE	UARS	Space Station
AMPTE/CCE	ATLAS-1, 2, 3	Attached Payloads
San Marco	Geotail	IKI-Equator
Rockets (15/year)	Wind	Rockets (18/year)
	Polar	Explorers (Melter)
	Cluster	Small Explorers
	Rockets (15/year)	
Active Plasma Experiments		
Rockets (5/year)	ACTIVE, APEX (USSR)	EOS Platform
	CRRES	Space Station Attached Payloads
	ATLAS-1, 2, 3	Rockets (7/year)
	TSS-1	Small Explorers
	Rockets (5/year)	

the research community for a variety of space measurements will be at least partially met with a combination of national and international missions. These missions are a testament to the efforts of many individuals who have worked to insure that worthwhile progress in the solar-terrestrial sciences would continue.

1.2 The Need for a Solar-Terrestrial Science Strategy Workshop

The Challenger accident has forced NASA and the space research community into a period of waiting and reappraisal. The most immediate effect of the accident has been the delay and then cancellation of a significant fraction of the shuttle flights planned to support solar-terrestrial science activities between 1986 and 1994. These included both manned science activities directly using the shuttle as well as unmanned satellites which were to have been launched with the shuttle. Decisions to cancel were based both upon the lack of flights available to solar-terrestrial science and because the cost to delay some flight investigations was prohibitive. New guidelines direct that the scarce resources offered by the shuttle should be employed for scientific research which is best served by the shuttle resources. This has led to an emphasis upon materials and life science research, at least in the near term out to 1994 in current NASA Office of Space Science and Applications (OSSA) Plans.

Looming in the future are possibilities for solar-terrestrial space investigations which take advantage of various space platforms related to the needs and plans of manned space flight. Possibilities include large, serviceable platforms such as the Earth Observation System in polar orbit, the Industrial Space Facility class of intermediate pressurized spacecraft capable of mounting external, attached instruments; and the much larger US/International Space Station (now known as the Freedom Space Station) with its full range of externally attached payload support facilities. There has also been increasing appreciation of the advantages of cooperative ventures with the Soviets and their Mir (Peace) space complex.

For the most part, the future flight plans developed within the Space Physics Division of OSSA have evolved without the use of space stations or large space platforms. As the plans of NASA's Office of Space Station matured, and political and funding support for this project appeared in Congress, it became increasingly clear that there was a need to evaluate the role such platforms could play in the future of solar-terrestrial science. Furthermore, in the light of the recent report from the National Academy of Sciences outlining space science goals for the 21st century, there is a need for creative thinking about far future programs exploiting the anticipated knowledge from the near-term flight programs of Table 1. In the current framework of the OSSA Space Physics Division, these far future missions exist within the realm of "in planning," and will require strong support from within NASA and the solar-terrestrial research community.

Another aspect of the future of solar-terrestrial science has evolved from the desire of the research community to participate in collaborative, international programs of research. Examples of successful collaborative undertakings in the past abound and the near-term missions listed in Table 1 are all the more valuable to the extent that they provide comprehensive views of solar-terrestrial phenomena. In recent months the European Space Agency (ESA), Canada, Japan, the Soviet Union, and the United States have engaged in various serious discussions about ways to promote international cooperation. All of the international participants in solar-terrestrial scientific research have plans for space flights that make important contributions to basic knowledge within the constitutive disciplines. These countries desire to develop formal relationships with the US for solar-terrestrial research.

1.3 The Decision to Organize a Solar-Terrestrial Sciences Strategy Panel Workshop

With this background, Dr. Stanley D. Shawhan, Director of the Space Physics Division at NASA Headquarters, decided it would be valuable for NASA to seek ideas and opinions about the future of solar-terrestrial science flight programs from active members of the research community. His desire was for a small group of experts to gather briefly to consider the long-range scientific needs of solar-terrestrial research in light of the opportunities offered by future flight programs. For the first time, these would include consideration of all types of space platforms, i.e., balloons, rockets, free-flying satellites, and the prospective variety of platforms supported by NASA's astronauts.

1.4 Participants in the STSS Workshop

Selection of individuals to serve as members for an ad hoc Solar-Terrestrial Sciences Strategy (STSS) Panel was made by Mr. W.T. Roberts (MSFC) and Prof. P.M. Banks (Stanford). The disciplines represented in the STSS Workshop were Solar Physics, Upper Atmospheric Science, Ionospheric Science, Magnetospheric Science, and Space Plasma Science. Twenty individuals were selected as official participants for the Workshop with approximately four persons assigned to each discipline. Table 2 provides the names of the panel members who attended the workshop meetings at Stanford University during the week of September 12 through 16, 1988. Other attendees who participated in the discussions are also listed.

Table 2. Attendees

Panelists	
Acton, Loren	Lockheed Corp.
Anderson, Hugh R.	Science Applications Int. Corp.
Baker, Daniel N.	NASA/GSFC
Banks, Peter M.	Stanford Univ., Chairman
Burch, James L.	Southwest Research Institute
Brueckner, Guenter	Naval Research Laboratory
Carignan, George R.	U. of Michigan
Chappell, C. Richard	NASA/MSFC
Chupp, Edward L.	U. of New Hampshire
Drobot, Adam	Science Applications Int. Corp.
Hastings, Daniel E.	Mass. Inst. of Technology
Hudson, Hugh S.	U of California, San Diego
Hudson, Robert D.	NASA/GSFC
Mende, Stephen B.	Lockheed Corp.
Nagy, Andrew F.	U. of Michigan
Raitt, W. John	Utah State University
Roberts, William T.	MSFC-PS02
Roble, Raymond G.	NCAR
Taylor, William W.L.	TRW Inc.
Walker, Arthur B.C.	Stanford University
Winningham, J. David	Southwest Research Institute
Speakers/Guests	
Balogh, Andre	Imperial College, London
Barfield, Joseph	Southwest Research Institute
Bartoe, John	NASA-Space Station
Benson, Robert	NASA/GSFC
Bonner, Thomas	Space Industries
Carter, David	NASA-SSU
Haskell, George	European Space Agency
Holemans, Jack	Wyle Laboratories
Jones, Vernon	NASA
Kendall, David	NRC Ottawa
Kropp, Jack L.	TRW Inc.
McEwen, D.J.	U. Saskatchewan
Parks, George	NASA-Code ES
Perry, Thomas	NASA-ES
Reeves, Edmond M.	NASA-EM
Sanders, Michael	Jet Propulsion Laboratory
Shawhan, Stanley D.	NASA-ES
Shepherd, Gordon	York U.-Canada
Vaughan, Arthur	Jet Propulsion Laboratory
Vondrak, Richard	Lockheed Corp.

1.5 Charter for the STSS Workshop

The workshop was presented with a charter for its activities by Dr. Shawhan. The overall goal of the workshop was to explore the future of solar-terrestrial science with emphasis upon those activities which would assume importance after 1995; i.e., after the major flight programs now regarded as being "Near Term" in Table 1 are in place and producing scientific information. Specific elements of the charter were to:

1. Establish the level of understanding to be accomplished with the completion of the current world-wide program of research in solar-terrestrial sciences
2. Identify the major questions to be answered by the future solar-terrestrial sciences research program as it might be if initiated within the next 10 years. An important input to this process was to be consideration of the National Academy of Sciences 21st Century report
3. Identify the space capabilities to be available to the future program and to provide input about the Space Physics Division's priorities for using these to accomplish its future scientific program
4. Map a program strategy to accomplish a future program of research in the solar-terrestrial sciences within the research community's perception of capabilities and constraints.

1.6 Organization of the Workshop

The STSS Workshop was organized with plenary sessions and discipline team meetings. The agenda for the workshop is given in Appendix I.

The first two days of the workshop were devoted to presentations from various NASA and industry personnel. The intent was to inform the workshop participants about current and near-term space flight platforms. In addition, Dr. Shawhan presented a detailed discussion of the current status of operating and near-term solar-terrestrial science missions.

The final 3 days of the workshop were organized around discipline meetings punctuated by general discussions with the entire group. This provided an opportunity for the ideas of each discipline to be evaluated in the context of the interests of the other groups. A final wrap-up session presenting the major recommendations from each discipline was held on the last day of the workshop.

1.7 Organization of the STSS Report

This report is organized along the lines of the discipline reports. Chapter 2 discusses the essential tools for solar-terrestrial sciences while the succeeding six chapters provide the results of the upper atmospheric sciences, ionospheric sciences, magnetospheric sciences, solar physics, and space plasma science, respectively. Chapter 8 contains a short discussion of issues brought forward by panel members during the discussions, but which belong in the category of general concerns rather than the specific plans or goals of the disciplines. Final recommendations of the workshop are given in Chapter 9.

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Chapter 2

Supporting Tools of Solar-Terrestrial Science

2.1 Introduction

Solar-terrestrial science is pursued by individuals and teams of workers situated in academia, research institutes, industry, and government laboratories. Progress in the field is made in various ways, but publication of results in scientific journals is the principal means of assuring that the knowledge gained from research is available to the public, now and in the future. In general, much of the research in the field is made via careful evaluation of data viewed in the context of fundamental physical principles as set forth in theoretical and analytical models, and computer simulations of physical processes. In addition, there is accumulation of knowledge expressed in the development of empirical or phenomenological models.

Experience gained over the past three decades of solar-terrestrial research indicates that advances in the field require a diversity of resources and that the health of the entire discipline depends upon a balance among these. To maintain the health of the discipline, NASA and other federal funding agencies concerned with solar-terrestrial research must work together to insure that the resources described in the following paragraphs are available in reasonable measure to support solar-terrestrial research endeavors.

2.2 Facilities and Tools

2.2.1 Ground-Based Facilities

Ground-based facilities are important for the progress of solar-terrestrial research. These include various types of optical and near-infrared observatories, atmospheric and ionospheric radars, radio transmitters, and other systems which provide for the monitoring of the upper atmosphere, ionosphere, magnetosphere, and the sun.

2.2.2 Balloons and Rockets

A continuous balloon and rocket program is essential to support innovative and small scale research activities and instrument development. The concept that the shuttle would be able to replace the NASA rocket program has proven to be false. It is clear that both rockets and balloons are essential to support the needs of the constitutive fields of solar-terrestrial science, in the next 20 years.

2.2.3 Spacecraft

Measurements in space lie at the heart of progress in space science. These make possible advances in knowledge through interpretation of models of the different processes underlying solar-terrestrial phenomena. The traditional platforms for accomplishing solar-terrestrial research have been free-flying satellites. New opportunities and difficulties have come with the space shuttle, and there are prospects for even more capable platforms to be flown in connection with the US/International space station. There is also an increasing need for in-situ active experiments.

During the workshop, panel members were asked to evaluate their science goals in terms of the following possible space vehicles:

- Small satellites
- Explorer class satellites
- Moderate class satellites
- Large, facility class satellites
- Space shuttle (up to 9 days in space)
- Extended duration space shuttle (up to 16 days in space)
- Serviceable platforms (e.g., the polar platform)
- Astronaut-tended facilities (e.g., the industrial space facility)

- Permanently occupied orbiting facilities (e.g., the Freedom Space Station)
- Lunar facilities, including occupied and automatic/robotic bases or sites
- Tethered platforms, including satellites of appropriate size.

2.3 Information Networks

The rapid growth of digital communication networks has expanded the appetite of the solar-terrestrial sciences community for frequent and rapid access to remote colleagues, data sets, computers, and other products of modern technology located at widely separated locations. There is no facet of solar-terrestrial research which has not benefited from the capabilities provided by NASA's Space Physics Analysis Network. Growth in capabilities of this and future networks is an essential ingredient of growth in productivity and capability needed to manipulate and distribute the large data sets which will come from the space observations of the next decade.

2.4 Computational Resources

The explosion of capabilities of small, medium, and large computers has revolutionized the methods of space science. The parallel growth in capabilities for information display has given even small research groups tools which formerly could be found only at major research laboratories. The ability to develop comprehensive computer models, to scan large data bases, and to view the results with multidimensional clarity has given impetus to greater progress in the field. In order for solar-terrestrial research to keep abreast of these developments, acquisition of these tools in a timely manner must be regarded as a fundamental aspect of the research program. The federal government must be convinced of the need to possess tools capable of meeting the challenges of the next decade's theories and high data volume scientific instruments.

2.5 Theory

Theory of fundamental processes is an essential part of solar-terrestrial research. The complex interactions of plasmas and magnetic fields, the passage of radiation through atmospheric gases, the interactions of VLF waves with trapped radiation belt particles, solar flares, and the transfer of energy through the geospace system are examples of the physical processes which must be understood. Theoretical studies of complex phenomena play an important role in the progress of the discipline and their support is essential to the well-being of the field. The NASA Solar-Terrestrial Theory Program has been a pathfinder in terms of scientific endeavor, and continued expansion of this type of work is an essential ingredient of the future.

2.6 Models of Solar-Terrestrial Processes

Theoretical models have a special role in solar-terrestrial science. Complete, comprehensive measurements of the physical state of the sun and terrestrial systems are impossible to obtain. Thus, the goal of space experiments and observations has been to obtain key information which could be used to shed light upon the underlying physical processes which can be incorporated into computer models and simulations. In the next decade, there will be a need to provide better general access to realistic computer-based models than has been the case in the past. Examples are the first principle models of high latitude plasma convection, ray tracing programs for a realisitic model of plasma in geospace, time-dependent models of magnetospheric convection, three-dimensional graphical models of the magnetosphere, and the evolution of solar plasma motions, magnetic field and coronal radiation during the course of a solar flare. In the past, such models have been the intellectual property of a few individuals who have shepherded their development. In the future, there could be substantial benefit to providing access to a wider community of research scientists.

2.7 Data Bases and Archives

Access to the results of previous observations and experiments in space is an essential ingredient of solar-terrestrial research. The data archives of the past are certain to become the fonts of new understanding about the sun and Earth in the next decade, if sufficient resources are provided to permit them to yield their treasures. The next decade will see increasing emphasis upon integrating old data with new theories, and it may be possible to confirm new concepts or relationships from space missions of the past. But, this idea suffers from the fact that it is easier to generate interest in pursuing new missions than it is to propose exploiting fully data from the past. The contributions from the past must be recognized for their potential to advancing knowledge of the solar-terrestrial system. NASA has the responsibility to work closely with representatives of solar-terrestrial science to reach the proper state of balance for the next decade.

2.8 Research Students

The thoughts and knowledge of the past are translated into the actions of the future through the training of students at colleges and universities. The Challenger accident and the consequent reduction in space flight experiment opportunities has meant that students who would otherwise have been attracted to the field have made other choices for their research careers. Another factor affecting the field has been the increasing time to consummate experimental programs. This has affected both students and young faculty who view their careers in terms of opportunities available with several years of effort. The steady flow of adequately trained, young scientists into solar-terrestrial research is essential to the health of the discipline and NASA is obligated to take this factor into account in planning for the future.

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Chapter 3

Report from Upper Atmospheric Science

Panel: G.R. Carignan, Chair; R.G. Roble, S.B. Mende, A.F. Nagy and R.D. Hudson

3.1 Introduction

The neutral thermosphere and the ionosphere are physically inseparable, although they are treated separately for the purpose of this report. Advancing scientific understanding of these regions demands an increased understanding of the relationships between the two as well as the couplings from the regions below and above. For the purposes of this report, the upper atmosphere is taken to embrace the region from the base of the mesosphere to the exobase, nominally 50 to 500 km altitude. During the 1970s, our understanding of the mid- and low-latitude thermospheric photochemistry was expanded greatly, largely through the measurements of the Atmosphere Explorers. Thermospheric dynamics have been studied subsequently from the Dynamics Explorer 2 satellite and from ground-based optical and radar observations. The information obtained from these experimental programs has been amplified through the use of large scale models, both physical and empirical. The combined approach enabled the most effective use of observations in deriving information on global dynamic atmospheric processes. Despite considerable progress in understanding the thermosphere, significant gaps remain in knowledge of its behavior. The lower thermosphere, because of a paucity of measurements, is still in need of exploratory study.

Progress in understanding the mesosphere has been much slower largely because of the relative difficulty of direct access and the difficulty thus far in remotely observing the region on a global basis. Our overall knowledge of the region has been pieced together from diverse and isolated measurements. The Upper Atmosphere Research Satellite (UARS) (scheduled for launch in 1991) will concentrate on stratospheric and lower mesospheric measurements. The upper mesosphere, like the lower thermosphere, is still basically unexplored. There is, however, considerable scientific interest in these regions because of nonlocal thermodynamic radiational processes, complex photochemistry, and gravity wave/mean flow interactions that dominates this region. The extent of the downward penetration of solar and auroral variability, that so dominate the thermosphere, into the mesosphere also needs to be determined.

3.2 Background

The thermosphere absorbs extreme ultraviolet (EUV) and UV radiation (wavelength, $\lambda<200$ nm) and, because of the absence of effective IR cooling mechanisms, is heated, giving rise to its name. EUV radiation and precipitating particles ionize the thermosphere and form the ionosphere. Energy and momentum are coupled into the upper atmosphere from the magnetosphere and waves and other disturbances propagating from below deposit their energy as they dissipate over wide ranges of altitudes. The ionospheric plasma is controlled through complex chemical and electrodynamic processes that operate throughout the region with rates dependent on plasma temperature and composition. Finally, the thermosphere becomes the energy sink for plasma. Neutral winds are driven by pressure gradients and ionospheric winds by electric fields of magnetospheric and dynamo origins, and these wind systems interact as they flow within each other. Joule dissipation from the differential motions of plasma and neutral gas is frequently the dominant heat source in some regions. Thermospheric winds redistribute the plasma directly through collisions and indirectly through dynamoelectric fields. In the mesosphere, exotic chemical processes operating in a complex dynamical field produce a highly variable state that begs for elucidation. Most of the operative processes appear to have been identified, but the sensitivity of the resultant state to the details of the interactions causes the models to yield descriptions that are far from reality. The upper atmospheric discipline stands in great need of additional observations, most of them well defined and within measurement capability, to enable the next increment in understanding. The complex suite of processes that operate in the thermosphere-mesosphere system is illustrated in Figure 3-1.

3.3 Outstanding Scientific Problems

The important advances in understanding of the upper atmosphere in the 1970s and 1980s, including recent results from modeling, have also identified a number of outstanding scientific problems. This report identifies four important problem areas. The scientific issues embedded in these areas are related and could have been posed as a greater number of problems, but the four-problem taxonomy seems to cover the main areas.

3.3.1 Mesosphere/Lower Thermosphere Interaction

Because this region is virtually unexplored on a global basis, fundamental questions exist about basic parameters and their variability as well as questions of important chemical, radiative, and dynamical phenomena. These include:

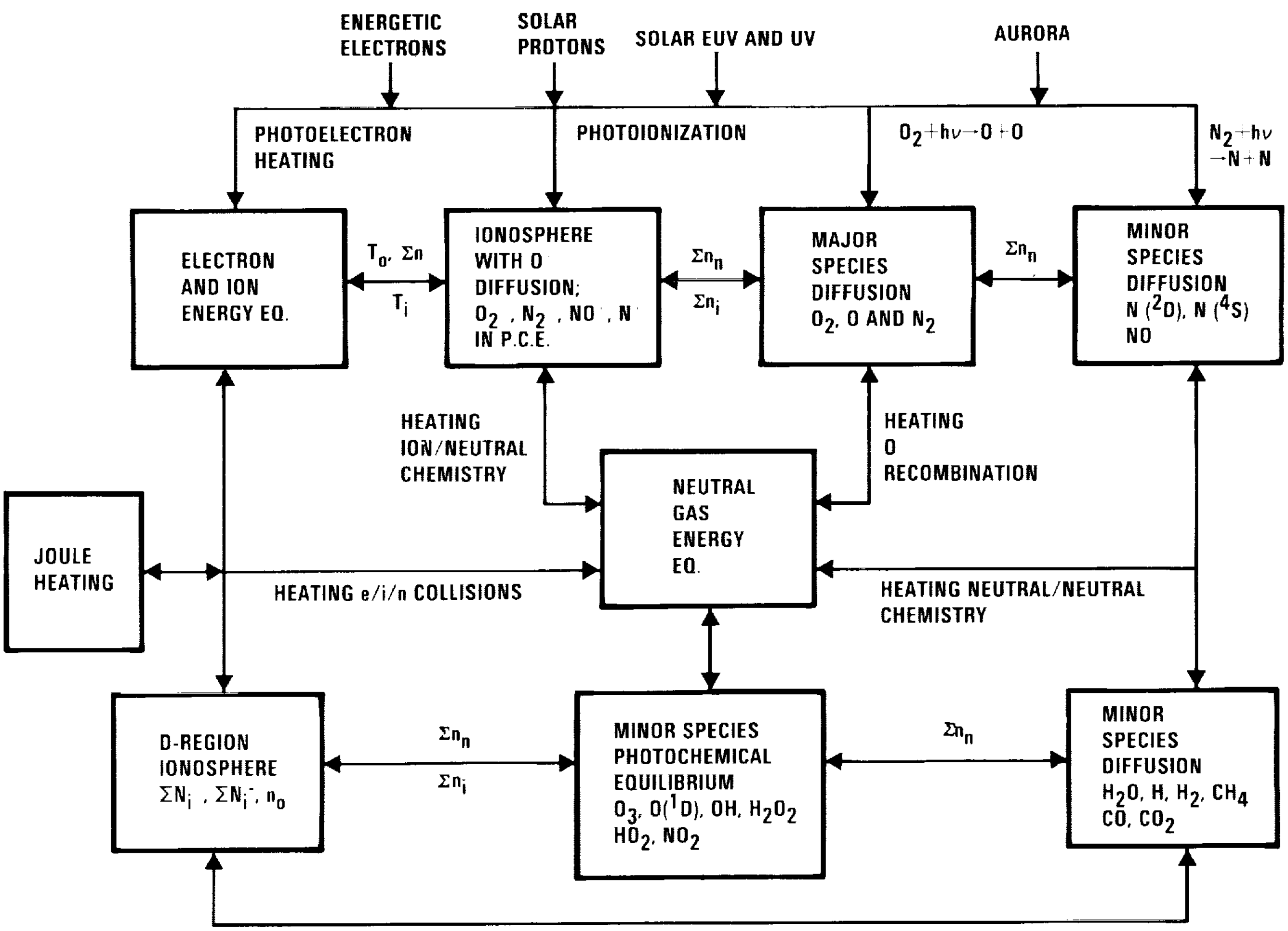

Figure 3-1. Diagram of Processes Operating in the Thermosphere and Mesosphere

- Basic structure of wind, temperature and composition
- Role of breaking gravity waves on energy and momentum budgets and as a mechanism for species transport
- Dissipation of upward propagating tides by molecular viscosity, thermal conductivity and ion drag
- OX, HOX and NOX chemical cycles and their response to solar radiative outputs, particle precipitation and disturbances from the lower atmosphere
- Role of nonlocal thermodynamic equilibrium infrared radiation from CO_2 and NO as cooling mechanisms.

The broad question of the chemical, radiative, and dynamic response of the mesosphere/lower thermosphere to solar and auroral variability is not well understood and experimental and theoretical studies should be made. The neutral winds in the region need to be measured in a global sense to guide modeling efforts with better measurement constraints. The basic structure of the temperature, composition and dynamics fields need to be defined to provide a baseline against which modifications from the increasing CO_2 burden can be evaluated.

3.3.2 Thermosphere/Ionosphere/Magnetosphere Interactions (<200 km)

A series of spacecraft programs, including OGO-6, AE-C, AE-D, AE-E, and the Dynamics Explorers, together with ground-based and other related observations have provided the data necessary to define most of the large scale processes operating in the upper atmosphere. Theoretical and numerical models have also been developed to provide a quantitative description of the region and its variability. The advanced state of our understanding notwithstanding, there are still a number of critical aeronomic processes that are highly parameterized because of a lack of the fundamental measurements that are needed to adequately describe them. Solutions to these problems could come from advanced measurement capabilities and increased insight into the nature of the region. It would be possible to significantly advance the state of knowledge of the interactions of the magnetosphere with the ionosphere and atmosphere while simultaneously complementing the International Solar Terrestrial Physics Program (ISTP). An advanced Explorer class aeronomy satellite will provide the observations necessary to describe the region that is the sink for most of the processes being investigated in the ISTP. This is a mission that begs to be undertaken.

Such a mission could be designed to answer several fundamental aeronomic problems, e.g., $N(^2D) + O$ quenching, $O + CO_2$ vibration excitation, and IR cooling. New instruments developed since the last flight opportunities should provide increased capability to resolve the fundamental aeronomic problems. Refinements in our understanding the chemical, radiative, and dynamical processes and their dependence on solar variability are needed and could be obtained by sophisticated instruments applied in effective measurement strategies. Altogether, a substantial scientific return would accrue from a modest mission that returns to the thermosphere during the epoch of ISTP.

3.3.3 Global Electrodynamics

The global electric circuit consists of three separate but interacting generators: (1) global thunderstorms maintain an Earth/ionosphere potential of 10^5 volts with a current of 10^3 amperes; (2) the ionospheric wind dynamo generates a potential of 10^4 volts with a current of 10^5 amperes; and (3) the solar wind/magnetosphere dynamo generates a potential of 10^5 volts and a current of 10^6 amperes. Understanding this global electric circuit is fundamental to atmospheric science and an integrated study of the total process is indicated. The study must include investigation of the relationship of the thunderstorm and lightning to upper atmospheric phenomena and include mapping of electric fields from thunderstorms to the ionosphere, from the ionosphere to the surface of the Earth, and between magnetosphere and ionosphere. The interaction of the neutral gas with the plasma and the resultant electrodynamic processes need to be quantified; new mapping procedures that incorporate disparate data sets can be of particular value in defining the morphology of the electrodynamic process which, through the use of models, can advance understanding of this interesting and complex phenomenon. Finally, the dependence of the global electrodynamics processes on solar variability must be understood.

3.3.4 Fundamental Process Measurements in the Space Environment

During the evolution of a scientific discipline, it inevitably becomes possible to pose questions of increasing detail and sophistication and it becomes necessary to attempt measurements of greater precision. In the recent past, exploration of the upper atmosphere has lagged behind the theoretical and associated modeling activities and has not exploited the latest technology available for space application. Atmospheric models require a large number of input parameters, and at the pioneering stage only a few of these are known. As the field matures, more parameters are known with better precision, but inevitably some are more poorly known than others. The experiment becomes an exercise in determining those least well known. This of course does not provide an adequate test for the model—what is needed is an overdetermined set of parameters, with sufficient accuracy. Whereas in the past, measurements with 50% accuracy could advance our knowledge, now the requirements may be for accuracies of 10% or better. It is, thus, possible to envision experimental programs that would advance our state of understanding through more precise quantification of states and processes through application of advanced remote and in-situ techniques. Some outstanding examples are:

- Solar, airglow and infrared radiation fluxes
- Excited and metastable species concentrations
- Ion/neutral and neutral/neutral rate constants
- Absorption and collisional cross sections.

Technological developments now make possible these more comprehensive and accurate measurements. In the optical field, array detectors provide vastly more efficient collection of spectral and spatial information. In terms of sources, fluorescence lamps, particle beams, and lasers provide excellent potential for active measurements. The optical field can be used in the local or remote sensing mode. The latter is practically the only way the mesosphere can be explored, but novel platforms such as the tethered satellite could be used to great advantage. A concerted effort to better define these and other fundamental attributes of the upper atmosphere in the actual thermosphere and ionosphere environment by in situ and remote measurements should be an important part of future exploration and could effectively exploit new technology and advanced spacecraft and missions.

3.4 Missions and Platforms

The outstanding scientific problems in the upper atmosphere can and must be studied by a wide range of remote and in-situ measurements, by missions to existing data bases, and through continued theoretical and modeling studies. The measurements could be provided by a variety of spacecraft—indeed, there is application for the full arsenal of planned platforms including space station, the polar platform, and tethered satellites—but the platform of choice tends to be Explorer-type free flyers where the science can fully drive the mission scenarios and where the perturbation environment is in the hands of the investigator. Table 3-1 shows, in a very simplistic way, how various platforms satisfy the needs of the experiments that would be undertaken to solve the scientific questions that have been posed. The spacecraft of choice is indicated by the double X.

Table 3-1. Applicability of Platforms to Experiment

Platform / Science Goal	Lower Thermosphere & Mesosphere	Global Electro-dynamics	Detailed Understanding of Thermosphere	Fundamental Aeronomic Processes
Space Station				
Attached Payloads		X		X
Polar Platform	X		X	
Co-orbit Platform			X	
Tethered			X	X
Man-Tended				XX
STS				
Space Lab				
Tethered	X	X	X	
Explorers	XX	XX	XX	XX
Rockets	X	X	X	
Balloons		X		
Ground-Based	X	X	X	X

The optimal missions for studying the identified problems need to be (and are being) defined by the scientific community. Two missions that emerge clearly from even a superficial analysis of the state of understanding of the upper atmosphere are (1) a mission that would remotely sense the mesosphere and lower thermosphere, and (2) a mission of one or two spacecraft that would combine in-situ and remote sensing in the thermosphere that would be in orbit during the ISTP program. These latter spacecraft would employ on-board propulsion, as did the Atmosphere Explorers, to give them access to a wide range of altitudes and a long lifetime. These two missions, supplemented by the application of attached payloads, tethered satellite measurements, and ground based measurements, would fuel a vital scientific enterprise in the upper atmospheric discipline.

3.5 Summary

During the 1970s and 1980s the thermosphere was explored extensively with the Atmosphere Explorer satellites, with the Dynamics Explorer 2 satellite, and through supporting observations from rockets, balloons and ground-based instruments. A major increment in our understanding of the thermosphere resulted from the analysis of the data accrued through these observations, but, as in any such complex endeavor, new questions were posed by the data that have not yet been answered. The mesosphere and lower thermosphere have been less thoroughly studied because of the difficulty of accessibility on a global scale, and many rather fundamental characteristics of these regions are not well understood. Given these circumstances, together with the great power of today's models and the availability of new measuring technology, substantial gains in our understanding of the upper atmosphere can be envisioned as a product of a relatively modest investment in experimental investigations and associated theoretical and modeling studies. Moreover, the ISTP program shows a compelling need for simultaneous measurements in these regions to define the state of the ultimate sink for many of the energetic processes that will be studied in the ISTP. Through careful planning, a major defect in the ISTP measurement suite can be eliminated by a mission that would also address most of the outstanding problems in thermosphere and mesosphere science.

A wide variety of measurement platforms can be used to implement various parts of the measurement strategy, but the major thrusts of the program would require Explorer-class missions. A remote sensing mission to explore the mesosphere and lower thermosphere and one or two Explorer-type spacecraft to enable a mission into the thermosphere itself would provide the essential components of a productive program of exploration of this important region of the upper atmosphere.

Chapter 4

Report from Ionospheric Science

Panel: W.J. Raitt, Chair; P.M. Banks, A.F. Nagy and C.R. Chappell

4.1 Introduction

The ionosphere is a region of the upper atmosphere in which the plasma population is dominated by thermal plasma with energies in the range 0.1 to 1 eV. It is commonly divided by altitude into regions delineated by slope changes in the altitude variation of the plasma density. In fact, these slope changes are related to changes in chemical and physical processes which occur at different altitudes giving rise to a nomenclature that describes the ionosphere in terms of D, E, F_1 and F_2 regions corresponding to increasing altitude from ~60 km to ~600 km. Above 600 km the thermal plasma still exists, but at mid and low latitudes it is dominated by light ions (H^+, He^+) and is sometimes referred to as the protonosphere.

Spatially the ionosphere can also be divided into two regions by latitude: the mid/low-latitude region bounded on average by the geomagnetic field shell with L=4, is called the plasmasphere, while poleward in each hemisphere is the region of the auroral/polar ionosphere. There is no clear altitude limit of the polar region as it merges into the magnetospheric tail. The two spatial regions are very different, the plasmasphere being characterized by quiescent thermal plasma while the polar ionosphere is dominated by a dynamic thermal plasma population.

Within the spatial boundaries of both regions referred to above, are a number of known features which have been observed by numerous techniques from both ground and space. These features together with the average altitude profile are summarized in Figure 4-1.

In the outline of ionospheric characteristics given above there have been references to average properties. This is an indication of yet another characteristic of the ionosphere; its temporal variability in both background characteristics and in the many features it exhibits. The time scale of the temporal changes varies from minutes in the polar ionosphere and hours for traveling ionospheric disturbances, to much longer diurnal, seasonal and solar cycle variations.

One clear message which stands out in this brief summary of the terrestrial ionosphere is that it is a complex region. Because of this complexity and high degree of variability in both space and time, we still do not understand the region well enough to predict its behavior accurately from time to time or place to place. The many years of ionospheric observations have given us a good qualitative picture of the ionosphere, but we are still a long way from an accurate quantitative model. However, in recent years the modeling of the ionosphere has moved ahead considerably to the extent that we are now lacking experimental observations to help quantify some aspects of the ionospheric models.

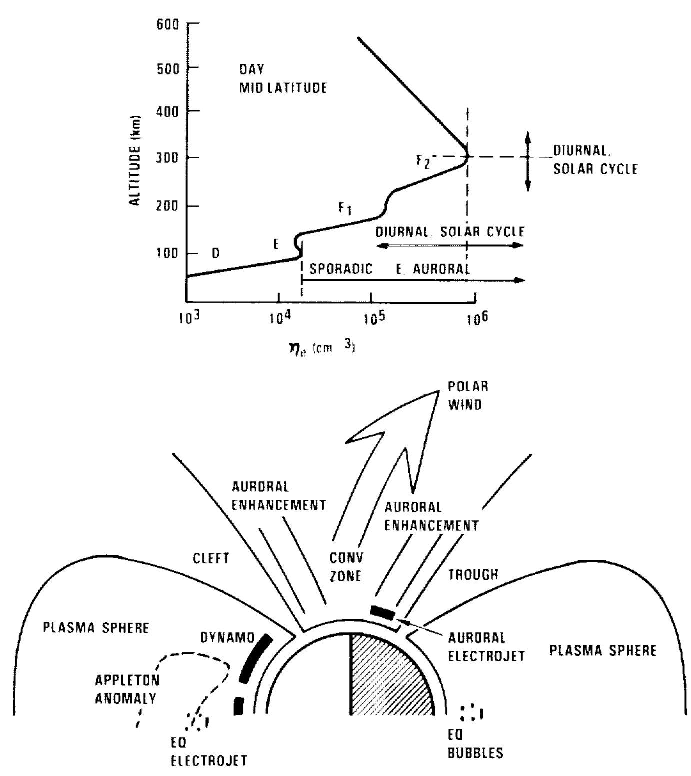

Figure 4-1. Some Known Ionospheric Characteristics

4.2 Importance of Ionospheric Studies

From its postulation in the early part of this century through its discovery in the 1930s until the present day, there has been continued interest in understanding the ionosphere. This interest ranges from the basic science involved in the formation and dynamics of the region through commercial and military interests involved with utilization of the ionosphere.

4.2.1 Basic Science

The ionosphere forms an interesting region in which plasma physics processes can be studied in an unbounded low pressure region of the upper atmosphere. The development of the steady-state ionosphere resulting from solar energy input and distribution as a result of a variety of physical processes has formed an ongoing interest for space plasma physicists.

4.2.2 Radio Wave Propagation

The ionosphere has an effect on radio wave propagation involving both reflection and transmission for frequencies which are below either the plasma frequency or the maximum usable frequencies, respectively. The characteristics of the ionosphere play an important role in the amount of energy that is reflected and therefore on the transmission characteristics of paths which utilize ionospheric reflection. This affects radio waves from the VLF to the very high frequency (VHF) ranges. As far as geosynchronous satellite communication is concerned, the transmission of data from the satellites is at a much higher frequency than the maximum plasma frequency encountered within the ionosphere, yet it is still affected by the ionosphere. The effect occurs in the very small changes in the transmission path at the S-band frequencies, often used for geosynchronous satellites which occur as a result of irregularities in ionospheric plasma density, particularly those close to the geomagnetic equator. These irregularities can result in small phase changes in the radio waves received on the ground, and this effectively sets an upper limit to the bit rate which can be used for transmission of data to and from geosynchronous satellites.

4.2.3 Atmospheric Interaction

The ionosphere plays a significant role in determining the properties of the neutral upper atmosphere. One of the ways in which it interacts is through ion drag effects whereby the plasma tends to remain attached to the geomagnetic field while the neutral gas is subject to forces which cause it to flow, resulting in collisions in which ions modify the flow of the neutral gas. The ion drag therefore affects both wind systems in the upper atmosphere and upper atmospheric waves. A consequence of the neutral atmosphere-ionospheric interaction force is to generate electric fields in the ionosphere resulting from charge separation as the plasma is forced to move relative to the geomagnetic field. These electric fields in turn can set up current systems which result in the atmospheric dynamo current system.

4.2.4 Magnetospheric Interaction

The ionosphere provides an impedance as a load for current systems which flow in the magnetosphere. Since the impedance for magnetospheric currents appears in the polar/auroral ionosphere it is subject to a great deal of variability resulting both from particle precipitation into the ionosphere and from the dynamic motion of the plasma in that region. In recent years it has been increasingly evident that the ionosphere also provides a source of plasma for the magnetosphere. Predictions suggested that light ions from the ionosphere could flow into the magnetosphere in the form of the so-called polar wind. More recently, studies of magnetospheric ion composition appear to indicate that there is a mechanism by which the heavier ionospheric ions, for example O^+, can reach the magnetosphere.

4.2.5 Noise Background

The presence of the ionosphere can provide a lower limit to the background noise of observations which are made through it. There is a continuous emission of optical fluxes resulting from ion chemical effects in the ionosphere. These are commonly referred to as the dayglow and the nightglow. In addition, in certain regions there is considerable radio noise background. This is particularly evident in the more dynamic polar regions of the ionosphere and is a result of plasma instabilities triggered by the variability of energy inputs into that region of the ionsophere.

4.3 Ionospheric Modeling

Ionospheric physics has made the transition from an exploratory phase to a degree of understanding in which predictability is a realistic goal. This capability will be provided by computer programs generally referred to as ionospheric models. In light of the importance of ionospheric studies described above, the models will play an important role in our understanding and utilization of the ionosphere as an important element of solar-terrestrial physics.

Ionospheric models provide a means of organizing and using ionospheric measurements for the wider community. The models give a predictive capability for global ionospheric properties as a function of geophysical parameters. Finally, they provide guidance on the type, frequency, and resolution required of ionospheric measuring systems which will be necessary to improve the validity of future models as they are developed.

At present, two general categories of models exist for describing ionospheric properties. Physics models, an example of which is the Utah State University Global Ionospheric Model (*Schunk,* 1988), and parametric models, an example of which is the International Reference Ionosphere (IRI) (*Rawer, et al,* 1981).

Physics models utilize a comprehensive description of the physical and chemical phenomena occurring within the ionosphere. As a result of this they place reliance on many measured coefficients describing plasma interactions, such as chemical rate coefficients and plasma collision frequencies. In order to predict the dynamic behavior of the plasma in the upper atmosphere, the models need to utilize magnetospheric particle fluxes and electric fields. At present these parameters are included on a somewhat arbitrary basis, because the linking of the particle and electric fields from the magnetosphere is not well established. In order to model the ionosphere on a global scale, using the techniques of numerical computation to solve the basic equations in the physical models of the ionosphere, massive computer resources are needed, and it is impractical to utilize such a model on a routine basis for a rapid prediction with a given set of input parameters.

Parametric models are based on taking a large amount of data and fitting a functional dependence of the measured ionospheric data, while taking into account a variety of measured geophysical parameters that have an effect on the ionospheric properties. The International Reference Ionosphere (IRI) provides a reasonable average description of the ionosphere, although comparison with specific measurements normally shows considerable deviation. The poorness of the fit is not uniformly distributed over the spatial and temporal domain. At low- and mid-latitudes a reasonably good description of the ionosphere is provided by the IRI, however, in the polar regions it is a long way from giving an accurate description.

In summary, the models provide a good guide to ionospheric properties but suffer in the physics case from inaccurate fundamental constants for some interactions and the very long time needed to calculate ionospheric parameters. The parametric models suffer from a lack of data in various regions of parameter space to the extent that, in the more dynamic regions of the ionosphere, they cannot provide a good description of the properties for all geophysical circumstances.

Although major advances have been made in our ionospheric modeling in recent years, it is becoming clear that the interaction of the ionosphere with the neutral atmosphere and the magnetosphere may not allow an independent model of the ionosphere to be used for predictions. The ultimate model of the Earth's upper atmospheric environment will eventually require a comprehensive atmosphere-ionosphere-magnetosphere model to adequately describe the region.

The ionospheric component of such a model, particularly at high latitudes or for small scale features at lower mid-latitudes, is dynamic enough that purely parametric models may not be a feasible solution. A hybrid model, which utilizes full physical descriptions but is organized to give rapid response to a given set of geophysical circumstances, may be necessary for providing accurate results on ionospheric properties with an adequate operational turnaround time.

4.4 Measurements Needed

4.4.1 Global Ionospheric Features

Some of the features of ionospheric models which require quantification are the spatial and temporal behavior of the ionosphere at various altitudes on a global scale. We are now in a position to predict this, but it is very difficult to utilize present or planned measurements to achieve an actual plasma distribution.

It is near or beyond the limits of technology to achieve this with the current height/space/time resolution of models. However, innovative imaging techniques are an area of instrument development that would greatly benefit ionospheric research in the future. By imaging we refer to the term in the most general sense including techniques other than optical imaging, both ground and space observation points, and the use of active imaging techniques.

In order to resolve the temporal and spatial behavior of larger-scale ionospheric features globally using optical techniques, the geosynchronous platform with maneuvering capability would be a good location for the instrumentation. However, polar cap measurements would not be well served by that location and an elliptical polar orbiting platform would be valuable in extending the observations of DE-1 and -2 and Viking, as well as providing coordinated observations from mid and low latitudes with the geosynchronous platform.

Other types of global imaging may require platforms nearer the ionosphere and could utilize radio wave techniques (ionosonde or incoherent scatter radar) or current sensing instruments to map out magnetic fields. If near-Earth orbits are used, the platforms should be in polar orbit to achieve global coverage, and multiple platforms would be advantageous to achieve some degree of global temporal resolution.

The value of any such imaging techniques would be greatly enhanced by coincident observations of solar flux (both photon and charged particle) from a solar observing platform situated outside the magnetosphere. In this way all aspects of solar variability in time and energy could be correlated to the global variation in the Earth's ionosphere.

4.4.2 Localized Ionospheric Features

Some aspects of ionospheric parameters are keyed to atmosphere, ionosphere and magnetosphere (AIM) coupling and involve small scale/rapid temporal changes which are less amenable to study by global imaging. Examples of such features would include small scale irregularities in density at both polar and equatorial latitudes, details of the convective flow pattern in the polar region and the ionospheric response to atmospheric gravity waves.

Our understanding of the ionosphere will be greatly improved if a systematic program of case studies is initiated to investigate these types of phenomena. Depending on the type of feature being studied, ground-based or any of a variety of space-based platforms could be used individually or in combination. However, as with global observations, the coincident measurement of solar input would immensely benefit the interpretation of the observations. Also, in the case of magnetospheric coupling effects, some coincident data on the configuration of the magnetosphere would be necessary.

4.4.3 Routine In-Situ Measurements

Global imaging will be biased largely to measuring the morphology of the ionospheric density characteristics, and, depending on the technique used, the accuracy of the observations would probably be less than that from in-situ measurements. Spatial resolution will also generally be lower. There is, therefore, a continuing need to gather background data on a variety of ionospheric parameters (plasma density, plasma temperature, plasma composition, and plasma flow) to extend the data base for coefficient determination used in parametric models of the ionosphere, and also to serve as a large collection of test data for physics models of the ionosphere.

A plan to routinely gather high quality in situ measurements over extended time periods should cover all geophysical conditions and last long enough to encompass at least one complete solar cycle.

Care in selection of instrumentation in terms of dynamic range and remote mode selection capability would enable the results to satisfy some aspects of the localized AIM coupling observations described above. Also, the flexibility of instrumentation is essential so that emphasis on a range of measurements can reflect the development of ionospheric models which the data is feeding.

In order to improve the predictive capability of ionospheric models, data collection and model development should proceed in parallel. This will prevent useful detailed measurements from being merely archived or compressed into a summary format.

4.4.4 Active Experiments

In the discussion of the utilization of ionospheric models it was pointed out that the physics models require a variety of coefficients describing basic physical and chemical processes involved in the formation and dynamic behavior of the ionosphere. Many of these measurements have been made in ground-based vacuum systems simulating the upper atmosphere, however, there is evidence that effects related to the dimensions of even the largest space simulation chambers can result in values of coefficients which are not applicable to the unbounded space environment.

In view of this, we believe it is important to institute a program to redetermine many of the key coefficients involved in ionospheric chemical and physical processes by controlled active experiments performed in the space environment. The large weight and power requirements of active experiments could be most readily accommodated on the space station, as long as contamination from the space station can be prevented from affecting the measurements. This type of experiment fits well into a concept of utilizing the space station as a spaceborne plasma laboratory in which the very careful, accurate measurements of interaction coefficients performed in ground-based facilities can be reproduced in the space environment.

4.5 Missions and Platforms

4.5.1 Present

Table 4-1 summarizes the requirements of an ionospheric component of a solar-terrestrial research strategy in terms of present resources

Table 4-1. Utilization of Existing Resources

Resource	Ground Based	Sounding Rockets	Unmanned Satellites				
			DE	ISIS-2	HILAT	San Marco	Viking
Global Ionospheric Features	M		M	M	M		M
Localized Ionospheric Features	H	H	H	H	H	M	H
Routine in-situ Measurements	M		M	H	H	L	M
Supporting Active Experiments	L	H					

H = High value
M = Moderate value
L = Low value
Blank = Not applicable

and programs. As indicated in the key, the various resources may have high (H), moderate (M), or low (L) applicability to the ionospheric studies, or they may be inapplicable.

Ground-based observations utilizing a variety of remote diagnostic devices are ongoing under funded programs. Because of the limited spatial extent of these facilities, even if networks are considered, they are of only moderate value in studying global ionospheric features. However, mobile or carefully located systems can be of great value in studying localized ionospheric features. Routine measurements are only moderately supported for the same reasons as the limitation on global measurements. However, if fixed site, local time behavior is needed, then a ground-based facility can be very valuable. Support of active experiments has a low level of applicability because the high energy required to be detectable on the ground precludes the rather precise, careful measurements of basic parameters being considered for supporting active experiments in this section. Ground-based resources are, however, valuable as remote diagnostics of active plasma studies performed in space.

Sounding rockets provide a valuable resource to the ionospheric community in their capability of providing short lead-time experiments to study localized phenomena, and to being suitable for certain categories of supporting active experiments. Clearly, the sounding rockets with LEO (low Earth orbit) altitude apogees are unsuitable for global imaging, and cost effectiveness would preclude using them for routine observations. An area in which sounding rockets will be of value is in the development of advanced instrumentation. The rocket payload would provide a useful low-cost method of obtaining initial space data as part of the planned development of a future operational instrument such as an innovative imaging system.

There are a few unmanned satellites which either are, or have the capability of, providing ionospheric measurements. DE, International Satellite for Ionospheric Studies (ISIS-2), High Latitude Satellite (HILAT), and Viking have moderate imaging applicability. The DE and Viking orbits and instrumentation favor polar and auroral imaging, but these are important aspects of ionospheric imaging and should provide very significant input for the future development of an optical imaging program. The ISIS-2 topside sounder represents a nonoptical category of imaging. It is classified as of moderate value because of the limited area viewed by the system, which requires extended periods of time to build up a global image. HILAT has similar limitations to DE, but is rather more restricted in imaging capabilities because of its lower orbit. The three polar orbiting satellites (DE, ISIS-2 and HILAT) all have the capability of contributing well to the study of localized ionospheric features and to the collection of routine in-situ measurements, although DE would be regarded as only moderate in the later aspect due to its high apogee. San Marco had a low inclination orbit and was therefore limited in the number of localized features accessible to it and in the extent of routine in-situ measurements. None of these relatively small unmanned vehicles is equipped to make supporting active experiments.

4.5.2 Planned

An assessment of future programs relevant to ionospheric studies, which are planned and funded, is provided in Table 4-2, using the same nomenclature for applicability as described above.

We assume that the ground-based and sounding rocket programs will continue and will support the same types of ionospheric studies described in the previous subsection.

There are several unmanned satellites in suitable orbits with appropriate instrumentation for investigations in future funded programs, two of which are NASA supported. The NASA ISTP polar satellite will provide similar ionospheric support to that described above for DE and Viking, however it will have the advantage of being part of a coordinated program with several other platforms providing important coincident stimulus and effect measurements. NASA is also developing the UARS program which, although primarily directed towards upper atmospheric studies, will include some in-situ ionospheric measurements to provide routine data measurements and studies of localized features.

Table 4-2. Utilization of Future Funded Programs

Resource	Ground Based	Sounding Rockets	Unmanned Satellites						Space Shuttle	
			EXOS-D	Cosmos Series	ISTP Polar	UARS	APEX	ACTIVE	ATLAS	TSS-1
Global Ionospheric Features	M		M	M	L	M			L	L
Localized Ionospheric Features	H	H	H	H	H	H			M	L
Routine in situ Measurements	M		H	H	M	H				
Supporting Active Experiments	L	H					H	H	H	H

H - High value L - Low value
M - Moderate value Blank - Not applicable

The Japanese Space Agency plans to launch EXOS-D in February 1989 carrying a complement of instruments to measure the characteristics of the terrestrial ionosphere. The planned orbital inclination of 75 degrees will result in a wide global coverage to provide valuable routine in-situ measurements, and will take the spacecraft to those locations where many of the localized features of the ionosphere can be studied. The in-situ observation will be supplemented by a television imaging system and an ionospheric sounder.

The extensive unmanned satellite program supported by the USSR offers the prospect of supporting a number of the ionospheric objectives in the near and more distant future. It is often difficult to get preliminary information on the payload composition of satellites in the Cosmos series. However, it is believed that these often carry plasma probes which have the potential of making them highly applicable to both the study of localized ionospheric features and routine in-situ measurements. Two other satellites planned by the USSR have had more prelaunch discussion than has been usual in the past. Apex is an unmanned payload planned for beam/environment interaction experiments, while Active will perform active wave experiments. It is not known how much passive observation these payloads will perform, but they will have high applicability to supporting experiments related to basic ionospheric physics.

There are two planned space shuttle experiments which will have some applicability to ionospheric studies. The ATLAS payload, due to fly in late 1990, will carry an imaging UV spectrometer (ISO) capable of making remote observations of ionospheric chemistry processes, an electron beam/plasma generator experiment (SEPAC) to perform active plasma experiments in the LEO environment, and an atmospheric emission photometric imager (AEPI) capable of supporting the active experiments. The TSS-1 payload is scheduled soon after ATLAS in early 1991. TSS-1 will carry some ambient plasma diagnostic instruments both on the Orbiter and on the deployed satellite. Its applicability to natural ionospheric studies is low because of the outgassing effects at the Orbiter end and, when the satellite is deployed, the high induced electromotive force (emf) in the conducting tether. In both cases the orbital inclination limitations imposed by a KSC launch restrict their usefulness for global studies, and the short duration precludes significant additions to a routine in-situ data base.

4.5.3 Future

As we look beyond planned missions to the more distant future, in which the existence of both man-tended platforms and permanently manned space stations becomes a reality, it is important to assess the value of these platforms and, if necessary, indicate how they will need to be supplemented by other space platforms to achieve the measurements necessary to have an ionospheric studies component in future solar-terrestrial observations. In order to successfully utilize the space station it will be necessary to have some resources and platforms available well ahead of the space station; in fact, in the very near future.

Table 4-3 summarizes the platform requirements in the near and more distant future. We anticipate ground-based and suborbital programs will continue and be utilized in much the same way as at present. However, with the greater load and power capabilities of a space station, it will be very important to have more readily available options to use high lift capability rockets to test some of the space station instruments before commiting them to that facility.

A new resource appearing in Table 4-3 is the existing ionospheric data bases acquired over most of the era of in-situ space science. Funded programs to revisit these data bases with our present and future capabilities in data handling and model interpretation would result in significant scientific value from a planned and adequately funded "mission to data."

The proposed small explorer class satellites will provide valuable platforms both for gathering data for model improvements and also for studying the characteristics of localized ionospheric features. Since these aspects of future ionospheric work are not well covered by space stations (except by use of tethered payloads) their utility could well go into the space station era by several years. The small size, low power, and restricted telemetry capacity limit the usefulness of these platforms in the areas of global imaging and active experiments.

Custom designed large satellites probably offer the optimum payload configuration for ionospheric measurements. Such platforms will enable imaging experiments to be placed in optimum orbits for resolution of ionospheric features, and they will also have the volume, power, and telemetry capabilities to group logically related instruments needed to study both stimulus and effect or, in other words, solar-terrestrial coupling effects. The value of these platforms to supporting active experiments in this area of study is rather more limited because of the removal of man from the loop.

Should a lunar base be established, then it would have considerable potential as a location to mount global imaging facilities. The distance may be too great for fine resolution of spatial/temporal effects in the ionosphere, but if techniques could be devised to image magnetospheric processes, then it would be well situated for those studies. There is some potential for performing active experiments at a lunar base. Since the

Table 4-3. Utilization of Planned and Proposed Future Resources, Ionospheric Programs Unfunded

Resource	Existing Data Bases	Ground-based	Sounding Rockets	Explorer Class Satellites	Large Satellites	STS	Lunar base	Space Station: Manned	Space Station: Man Tended	Space Station: Co-orb*	Space Station: Polar	Space Station: Tethered Payload
Global Ionospheric Features	M	M		M	H	L	H	L	L	L	M	M
Localized Ionospheric Features	H	H	H	H	H	L		L	M	M	H	H
Routine in-situ Measurements	H	M		H	H			L	M	M	H	H
Supporting Active Experiments	L	L	H	L	M	H		H	H	M	M	M

H - High value
M - Moderate value
L - Low value
Blank - Not applicable

*Co-orbital platforms

ambient environment has an extremely low pressure, it is possible to consider not only launching a controlled source of energy into the outside environment, but also to release material to simulate the upper atmospheric species, again under carefully controlled conditions.

The limited flight time, generally low orbital inclination, and contaminated environment of the STS reduce its value in carrying experiments to make global, local, or routine ionospheric measurements. The load carrying, power, and telemetry capabilities of STS do, however, provide it a role in performing active space plasma experiments which could be devised to support the basic ionospheric physics going into the computer models.

The space station heading includes several optional platforms associated with the NASA permanently manned facility. The manned space station suffers from many of the disadvantages of the STS in making ionospheric measurements, however, it is immersed in the space plasma and could conceivably be used to gather routine in-situ data, albeit from a restricted latitude range. The man tended and co-orbiting platforms have similar restrictions to the manned facility except it is anticipated that the lack of life support systems will result in a cleaner environment for plasma measurements.

A polar platform is a more attractive option because of its global coverge and clean environment. Global features will be sampled on a daily basis, but imagery will be less well supported due to its expected low operational altitude. Active experiments will be somewhat less well supported than from manned systems because of the completely remote operation which would be required.

A final type of space station associated payloads will be tethered platforms. The utility of these payloads to support ionospheric measurements is improved over the manned structure because of the ability to deploy them out of the contamination region around the space station. However, orbital inclination and altitude limitations will restrict the coverage of the measurements. A further consideration in this technique is the electrodynamic effect associated with the conducting tethers. While this is of interest in its own right as active experiments, the electromagnetic fields associated with them have a possibility of intruding into the measuring region and affecting the ionospheric plasma measurements.

4.6 Summary

The general strategy to advance our knowledge of the ionospheric component of the solar terrestrial system should consist of a three-pronged attack on the problem.

Ionospheric models should be refined by utilization of existing and new data bases. The data generated in the future should emphasize spatial and temporal gradients and their relation to other events in the solar-terrestrial system. In addition, the time scale over which data is acquired should address the long-term solar-cycle effects and possible man-made pollution of the ionosphere. The goal of this aspect of the approach to ionospheric studies is the provision of an accurate predictive capability both for operational reasons and for utilization in basic studies of solar-terrestrial interactions.

In parallel with the improvement in modeling, it will be necessary to initiate a program of advanced instrument development. In particular, emphasis should be placed on the area of improved imaging techniques. The development of these techniques should not initially be tied to a definitive space mission, but should progress to that goal through an orderly development involving laboratory testing and spaceborne test flights to reach the stage of operational deployment of the instrument.

The third general activity to be supported should be active experiments related to a better understanding of the basic physics of interactions occurring in the ionospheric environment. The use of controlled energy fluxes in various forms in concert with local and remote diagnostic probes will enable naturally occurring interactions to be characterized over the wide dynamic range which occurs in the solar-terrestrial environment.

An important aspect of the implementation of the three-pronged attack is the logical

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Chapter 5

Report from Magnetospheric Science

Panel: J.L. Burch, Chair; J.D. Winningham, H.R. Anderson, D.N. Baker, C.R. Chappell and W.W.L. Taylor

5.1 Introduction and Background

By the early 1990s, magnetospheric physics will have progressed primarily through observations made from Explorer-class spacecraft, sounding rockets, ground-based facilities, and shuttle-based experiments. The field is still dominated by in-situ measurements with remote imaging and active experimentation becoming more prevalent in recent missions. The global geospace science (GGS) element of the ISTP program is the first major new start in the field in over 20 years. Although the spacecraft are still in the class of large Explorers, there are two US spacecraft and instrumentation on a Japanese spacecraft. When combined with contributions to the ESA Cluster mission and vigorous ground-based and computer modeling programs, GGS will form the basis for a major US initiative in magnetospheric physics.

The scientific objectives of the GGS program involve the study of energy transport throughout geospace. The Cluster mission will investigate turbulence and boundary phenomena in geospace, particularly at high latitudes on the dayside and in the region of the neutral sheet at geocentric distances of about 20 earth radii on the night side of the earth.

After ISTP the achievement of further important objectives in the discipline will rely on the development of a three-pronged approach to magnetospheric experimentation combined with a complementary theory and modeling program. The three necessary techniques are: (1) the use of advanced photon and particle imaging of all of the plasma populations of the magnetosphere and the global convection patterns; (2) the use of arrays of spacecraft measuring crucial parameters in carefully selected regions of the magnetosphere; and (3) the use of active probing and stimulation of magnetospheric plasmas. The simultaneous use of these three techniques will be needed along with a real-time modeling capability, which is capable of transforming the measurements into a global perspective of magnetospheric processes.

5.2 Current State of Knowledge

The interaction between the solar wind and the magnetosphere is characterized by a continual gradation of disturbance levels that manifest themselves through auroral displays and the intensities of the driving currents of the system. There is some doubt now that there exists a magnetospheric ground state. If there is, it corresponds to conditions of a nearly zero north-south component of the interplanetary magnetic field (IMF).

Increasingly southward components of the IMF lead to substorm activity with extensive auroral displays along an expanded auroral oval. Substorm initiation is associated with a disruption of the magnetotail neutral sheet and a diversion of neutral-sheet current into the ionosphere. The location of the disruption, the role of magnetic reconnection, and the formation of plasmoids that propagate down the tail are topics that are presently under active investigation.

Northward IMF components lead to a strikingly different disturbance state of the magnetosphere. The auroral oval shrinks and moves poleward and the polar cap itself becomes the site of increasing auroral activity in the form of polar cap arcs and, at times, the theta aurora. The field-aligned currents, which drive magnetospheric convection, change their global characteristics substantially, leading to sunward convection in the polar cap. If anything, auroral activity at dayside high latitudes, near the cusp, becomes more active as nightside auroral activity subsides.

The transfer of solar-wind energy into the magnetosphere for both northward and southward IMF appears to proceed, at least in part, through a process involving magnetic reconnection. For southward IMF, this process results in the formation of flux transfer events, by which solar wind and magnetospheric plasmas intermingle and a convection electric field is imparted to the high-latitude magnetosphere. Flux transfer events appear to form at low latitudes along the dayside magnetopause. Multipoint observations in that region will be required for an improved understanding of this very important magnetospheric phenomenon.

One of the most fundamental problems of magnetospheric physics is the acceleration of auroral particles. It is widely held that electric-field components parallel to the magnetic field are responsible for the downward acceleration of auroral electrons and the simultaneous upward acceleration of ionospheric ions. The parallel E-fields seem to occur preferentially in regions of strong field-aligned currents associated with convective shear reversals in the magnetosphere and ionosphere. Whether the parallel electric fields are localized in altitude as double layers or are greatly extended in altitude is not known. Definitive new information on the auroral potential structure will require the use of multipoint measurements at altitudes of several thousand kilometers above the auroral oval. Active probing of the potential structures with test particles will be necessary for the unambiguous measurement of the parallel E-fields because they tend to occur in regions of strong perpendicular components.

Much has been learned recently about the sources of magnetospheric plasmas. The ionosphere is, of course, the source of thermal plasma throughout the magnetosphere. The ionosphere and the solar wind are both important sources of the more energetic plasma. Recent data has shown that the cusp region is not only the prime site of entry of solar-wind plasma into the magnetosphere but it also is possibly the strongest source of ionospheric plasma to the magnetospheric regions beyond the plasmasphere. Turbulence in the cusp ionosphere, coupled with strong antisunward convection emanating from the cusp region, leads to the formation of a cusp ion fountain, which feeds accelerated ionospheric plasma to the entire outer nightside magnetosphere. We need to know whether or not this ionospheric plasma is transported to the neutral-sheet region of the magnetotail where it would become an important constituent of the plasma sheet and ultimately the ring current. An answer to this question will require the measurement of thermal plasma composition in the equatorial region of the magnetotail, particularly in the region within about 20 Earth radii down the tail.

Typical magnetospheric plasma distributions contain significant amounts of free energy in the form of beams, loss cones, and other types of velocity-space density gradients. This free energy leads to wave growth and significant wave-particle interactions, which result in the acceleration of electrons and ions and in their precipitation into the atmosphere. Significant new data has been obtained recently on the processes involved in the generation of auroral kilometric radiation (AKR) and auroral hiss as a result of spacecraft that have probed the auroral acceleration regions directly. AKR appears to be generated within plasma density cavities with energy derived from electron loss-cone distributions. A relativistic effect known as the cyclotron maser instability is generally accepted as the generation mechanism. As yet there is no general agreement on the source of auroral hiss emissions except that they also could be generated by electron velocity-space density gradients, possibly associated with the electron "hole" distributions, which are produced by a loss-cone distribution in the presence of a parallel electric field. Other important wave modes, such as ion cyclotron and lower hybrid waves, with frequencies near the ion gyrofrequency have been invoked for the transverse acceleration of ionospheric ions (ion conics) and the parallel acceleration of electrons (suprathermal bursts).

5.3 Science Goals

The ISTP program will include the following major spacecraft missions:

- Wind, a phased mission using double-lunar-swingby and L1 halo orbits to sample the interplanetary medium upstream of the magnetosphere.
- SOHO, a solar observatory at L1;
- Polar, a phased mission using elliptical polar orbits with apogees of 6 and 9 Earth radii. The spacecraft will carry visible and ultraviolet auroral imaging and a comprehensive plasma and fields payload.
- Geotail, a Japanese spacecraft with plasma and fields instrumentation for the in situ sampling of the near and distant geomagnetic tail using double-lunar-swingby orbits extending to distances beyond 200 Earth radii.
- Cluster, four ESA spacecraft in a tight array for study of turbulent phenomena in a 2 by 20 Earth polar orbit with the initial apogee at the equator.

The Soviet Union and possibly other countries will also be contributing spacecraft to the ISTP program.

The overall science objective of the ISTP program is the study of large-scale energy transport in geospace with contributions to smaller-scale turbulent phenomena from Cluster. Aside from the auroral imaging on Polar, all the ISTP spacecraft will use in-situ measurements.

The next significant step in magnetospheric physics beyond ISTP will require the use of global imaging of magnetospheric plasma and energetic particle populations and further use of spacecraft arrays for studies of the spatial structure and temporal evolution of major particle acceleration and energy dissipation processes. The imaging techniques and the use of spacecraft arrays should be employed simultaneously for greater effectiveness.

Because of the lack of global plasma and particle imaging capability on ISTP and the single orbit of Cluster, which will not allow for multi-point measurements near the subsolar magnetopause, in the auroral acceleration regions, or in the neutral sheet within and beyond ~ 20 Earth radii, the following science questions are not expected to be answered satisfactorily by ISTP:

- What processes are responsible for energizing the magnetosphere in the subsolar region of the magnetopause and for phenomena such as flux transfer events, which result from these interactions?
- What is the three-dimensional topology of the magnetosphere and its various plasma boundaries, current systems, and convection patterns, and how do these configurations evolve during magnetospheric substorms?
- What is the three-dimensional structure of the auroral potential structure and how does it evolve in time?
- How is the neutral sheet within and beyond 20 Earth radii disrupted during substorms?

5.4 Magnetospheric Science Missions

Two types of missions to the Earth's magnetosphere will be required after ISTP. The first of these is the global imaging mission, which was advocated in the recently published National Academy of Sciences publication on space science in the twenty-first century. Recently developed approaches to the imaging of plasma populations using photons (e.g., helium 304 Å emissions) and energetic neutral particles (produced in charge-exchange interactions), along with established auroral-imaging techniques, hold the promise of global imaging of the magnetosphere. In addition to auroral imaging from elliptical polar orbits (as with the Polar spacecraft) there is also the possibility of imaging from lunar-based observatories or spacecraft in orbit about the Lagrangian points, particularly L4 and L5. Figure 5-1 illustrates some possible imaging missions.

The second class of missions is the multi-point mission involving arrays of identically instrumented spacecraft with either large or relatively small spacing. An example of a large array would be a set of "current probes" deployed to map the current systems throughout the magnetosphere. Such a network, which was also described in the NASA report on space science in the twenty-first century, would have to be augmented by closely spaced arrays moving through the large-scale network to measure the spatial structure of the electric and magnetic fields,

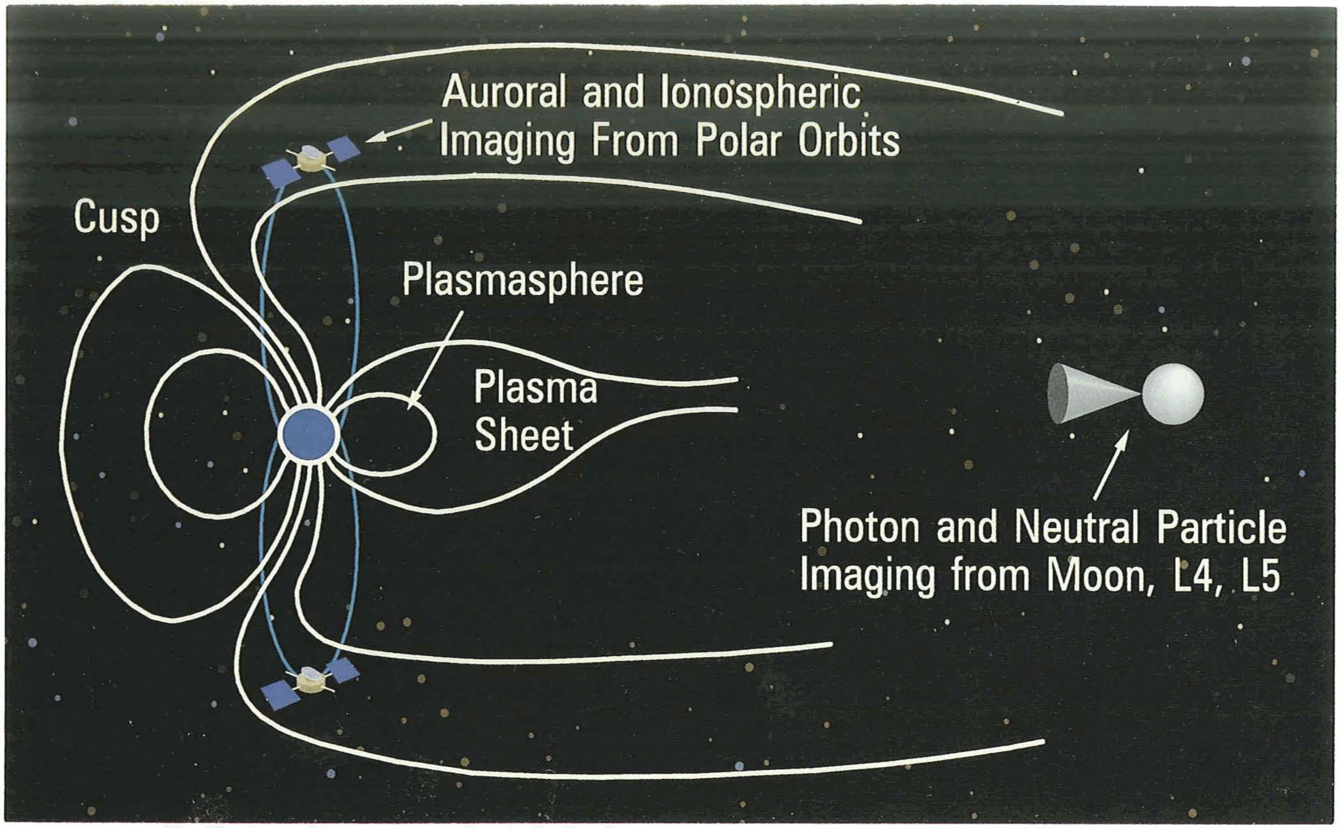

Figure 5-1. Imaging of Auroras, Plasmas, and Energetic Particles

which are the primary observables associated with the current systems.

Indeed, relatively closely spaced arrays (as in Cluster) are needed for the detailed probing of the important plasma phenomena in the magnetosphere. Primary targets for spacecraft arrays with identical plasma and field instrumentation are the low-latitude dayside magnetopause, the auroral acceleration regions at altitudes of 1 to 2 Earth radii along field lines, and the neutral sheet within and beyond 20 Earth radii (the Cluster apogee). Figure 5-2 shows the current probes and various spacecraft arrays in critical regions of the magnetosphere.

Other types of platforms, as well as ground-based observatories, are also applicable to the future magnetospheric science goals. Table 5-1 is a matrix showing the various platforms and the four outstanding science questions from Section 5.3. The double Xs indicate a primary contribution and the single Xs a valuable contribution. The use of manned platforms at low altitudes and inclinations is envisioned as involving active plasma experimentation as discussed further in Chapter 7 (Space Plasma Science).

5.5 Data Analysis, Modeling, and Theory

Data analysis, modeling, and theory need to be increasingly integrated to make the most effective use of the flight opportunities, to identify unresolved issues and thereby assist in planning future research requirements. On the time scale of the turn of the century, following implementation of ISTP and other programs, we expect to be in a position to attempt a fully quantitative treatment of the phenomena observed in the Earth's magnetosphere.

We assume that by 1995, an internationally based program will have been put in place, with the objective of integrating the scientific output of the US, European, Japanese, and Soviet spacecraft which will explore the different regions of the magnetosphere. In addition to the extended operations and data analysis phases for each of these missions, we recommend a worldwide coordinated effort to combine the global data

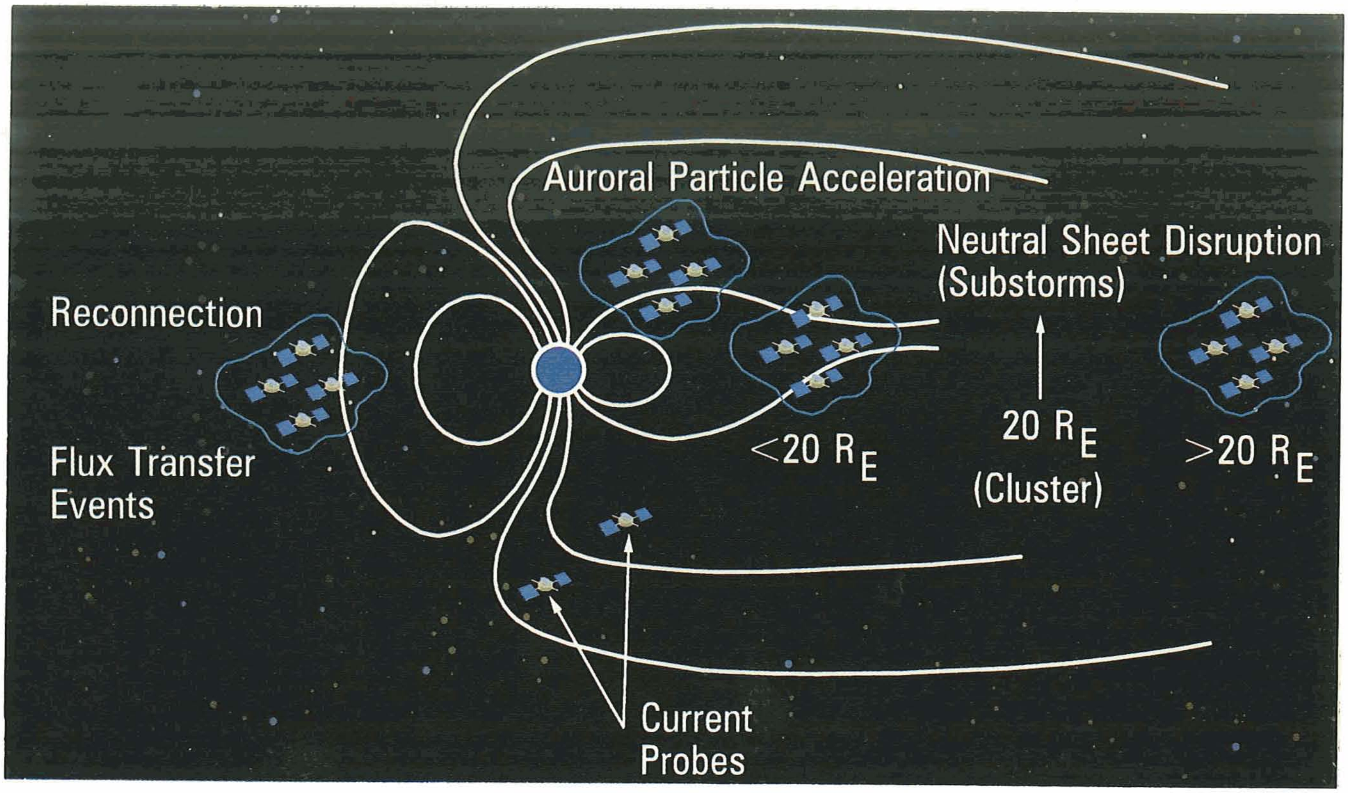

Figure 5-2. Arrays of Spacecraft Needed for Study of Major Acceleration and Energy Dissipation Processes

Table 5-1. Magnetospheric Science Missions

	Science Goals			
Platform	**Energy Transfer at Subsolar Magnetopause**	**3D Structure**	**Neutral Sheet Disruption**	**Particle Acceleration**
Imaging Observatories	X	X		
Multipoint Spacecraft	X X		X X	X X
Manned Station			X X	
Polar Platform		X X		X X
Space Shuttle	\ X		X X	
Sounding Rockets			X X	
Ground Based		X X		

XX denotes primary mission, X denotes secondary mission

Imaging observatory would view HeII 304 Å and energetic neutral atoms

Chemical releases in crucial regions could enhance imaging

Injection of test particles is needed for probing of acceleration regions

Continuous monitoring of the interplanetary environment is needed for all missions sets and carry out the scientific analysis of the data across all the missions. This requires a new initiative, a new way to organize and manage the scientific optimization of multi-spacecraft international flight programs. One approach would be to have an official data analysis mission, which would utilize essentially the same management and methodologies as a flight program.

The knowledge thus acquired would be unprecedented in quality and quantity, and would provide the basis for:

- A truly quantitative three-dimensional modeling capability
- The full-scale merger of data analysis and theory systems.

Parallel theory and modeling efforts, in close cooperation with the development of data analysis techniques, should lead to:

- Development of a magnetospheric global circulation model
- Simulation of physical processes at all scales
- Use of local, high-resolution particle-code simulations to analyze and interpret data from clusters of spacecraft
- Ability to "fly" spacecraft through MHD (magnetohydrodynamic) and single-particle computer models and generate a simulated data set.

5.6 Advanced Instrument Development Program

The lead times and hence the costs of future magnetospheric missions could be measurably decreased through an advanced instrument and spacecraft development program. An effective program would include the following elements:

- Fund as an identified line item in NASA budget to stress its fundamental importance.
- Develop instruments to engineering model level. Define refined costs through this approach with the goal of lowering cost and shortening delivery time.
- Fund competitive studies of standardized low, medium, and complex spacecraft. Implement one of each based on competitive selection to establish accurate cost and interface models.
- Fund parallel systems research (to above items) of present system of implementing missions. The synergistic goal would be to reduce costs by identifying cost/benefit payoff of present methodologies with elimination of non-beneficial elements.
- Base selections on relevance to mission plans through 2015.
- Specific recommendations would be to (1) emphasize remote sensing of magnetosphere for global physics, and (2) develop low cost, standard cluster spacecraft to examine relevant microphysics.
- Correlate with theory and modeling programs to establish key regions and parameters to be targeted for verification and refinement of models and theory.

5.7 Crucial Elements of the Future Magnetospheric Physics Program

Accomplishment of the science goals of the future in magnetospheric physics will require the development of several crucial programs and capabilities, including:

- Photon and/or neutral particle imaging of the aurora and of all the plasma populations of the magnetosphere
- Arrays of low-cost spacecraft measuring critical parameters in carefully selected regions
- Active probing and stimulation of magnetospheric plasmas
- A vigorous theory and modeling program
- Missions to data bases
- An advanced instrument and spacecraft development program
- Continuous solar-wind monitoring.

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Chapter 6

Report from Solar Physics

Panel: A.B.C. Walker, Chair; L. Acton, G. Brueckner, E.L. Chupp, H.S. Hudson and W. Roberts

6.1 The Nature of Solar Physics

The sun provides a laboratory in which the interaction of plasma, magnetic fields and gravitational fields occurs on scales, and in regimes of temperature and density which cannot be duplicated in the laboratory. The phenomena which occur on the sun, such as the solar activity cycle, the generation of energy by thermonuclear reactions, the nonthermally heated corona, the acceleration of particles to very high energy, and the generation of the solar wind are challenging and fascinating problems in fundamental physics. The core of the discipline of solar physics is the study of these phenomena. We have made significant progress in identifying the physical laws responsible for these phenomena, and in formulating more precisely the fundamental questions which must be addressed to achieve a deeper understanding of them.

The sun also represents the major source of energy in the solar system, and controls, or strongly influences, events in planetary atmospheres, magnetospheres, and ionospheres, via direct irradiation, and via the extended atmosphere of the sun, the heliosphere. The problems presented by the interaction of the sun with the Earth, in particular, solar-terrestrial relations, are of great importance. These problems are no less challenging or rewarding than those associated with the sun itself. They do, however, require solar observations of a different nature from those required to address the physics of the sun itself, along with measurements of the magnetospheric, ionospheric, or atmospheric phenomena of interest.

The sun is the only star that we can study in detail; the comparison of the sun and of other stars (especially with sun-like stars at different stages of evolution, or with stars of different mass or composition) is a powerful technique for stellar astronomy. The sun also represents a unique opportunity to study phenomena which we observe elsewhere in the galaxy, in sufficient detail to test fundamental physical laws. The comparative study of such phenomena on the sun and elsewhere in the galaxy or the universe can provide insights valuable both to the solar physicist and the stellar or galactic astronomer or cosmologist.

A complete and comprehensive solar program must embrace all four aspects of solar physics (Table 6-1); pure solar studies, solar-terrestrial studies, comparative solar/stellar studies, and the study of physical processes, such as particle acceleration, which play an important role in astronomical phenomena on many scales. The latter two aspects are sometimes referred to as "the study of the sun as a star".

The outer solar atmosphere becomes unexpectedly hot within the first several thousand km of altitude above the photosphere. This energization also impels the solar wind, which flows outwards to form the heliospheric cavity in the interstellar medium. The flow of the solar wind is regular and has continued over the lifetime of the sun, but it contains many complexities; these include a time variable neutral sheet, transient disturbances such as streamers, coronal mass ejections, and large scale shock waves, plus a component of zodiacal and cometary dust. In a sense this enormous volume (extending to at least 50 AU) should be considered to be an integral part of the volume of the sun, but one that is

Table 6-1. The Nature of Solar Physics

- "Pure" solar physics includes the study of:
  - Complex interaction of plasma, gravitational, and magnetic fields
  - The solar activity cycle
  - Coronal heating
  - Particle acceleration
  - Solar wind generation
- Solar-terrestrial relations make strong demands on our understanding of solar phenomena because:
  - Solar radiative and particulate fluxes energize the magnetospheres, atmospheres, and ionospheres of the planets, including earth
  - Understanding the nature and causes of solar variability is critical to modeling the variability of the earth's atmosphere, ionosphere, and magnetosphere
- Study of the sun as a star has important consequences for astrophysics because:
  - Activity cycles and coronae are common features of cool stars, therefore comparative studies of the sun and other sun-like stars are mutually beneficial
  - Many stellar and galactic phenomena (particle acceleration, winds, flares, etc.) can only be studied in detail by observing their solar manifestations

generally optically thin and that has interesting intrusions, such as cosmic rays, the planets and their magnetospheres; comets, etc.

The steady and varying properties of the heliospheric plasma have many direct effects on the terrestrial-plasma environment, ranging from the polar auroral displays to the generation of Earth currents during major magnetic storms. The structure of the heliospheric plasma modulates the galactic cosmic rays, as well as transporting the solar energetic particles directly to Earth. In these ways the detailed physics within the heliospheric volume plays a role in determining the terrestrial environment which may be as significant as the consequences of the solar irradiance variability.

The present status of heliospheric physics can best be described as "on hold" between missions; we are hoping for substantial progress via SOHO/Cluster and the Wind spacecraft, plus perhaps new selections of Explorer or small Explorer experiments, but there is very little observational activity from space at present. Indeed, the future missions that have been selected are not optimal for the specific needs of solar-terrestrial research, but are instead oriented more strongly towards the "pure" branches of solar physics and/or space plasma physics.

Future missions optimized for understanding the solar-terrestrial relationships should emphasize the synoptic (i.e., stable, long-term, systematic measurement of the most significant parameters). This must include extensive remote sensing or imaging data since truly comprehensive multipoint observations of heliospheric structure would be prohibitively expensive in terms of numbers of spacecraft.

6.2 Current Understanding and Anticipated Near-Term Progress

6.2.1 A Brief Review of Recent Advances in Solar Physics

In the past decade, observations of the sun from space and from the ground have led to profoundly important and frequently unexpected discoveries which have greatly enhanced our knowledge of solar phenomena and of their connections to the other disciplines cited above. Among the most significant of these discoveries are:

- The first direct experimental confirmation of the central role played by thermonuclear processes in stars, by the successful detection of neutrinos from the sun(1).

More importantly, the disagreement of the observed neutrino flux with that predicted by standard solar models has resulted in the planning of new observational approaches to test the assumptions and the detailed predictions of the resultant models more directly.

- The discovery that the 5-minute oscillations of the sun are a global seismic phenomenon that can be used as a probe of the structure and dynamical behavior of the solar interior(2).

The study of these oscillations, and of longer period oscillations whose existence has been recently reported, provides a unique and powerful method to probe solar (and therefore stellar) structure and evolution, and the transport of energy and the generation of magnetic fields in the sun's convection zone (and therefore in the convection zones of cool stars). More recently, Space Lab II observations have demonstrated the persistence of flow fields at mesogranulation and granulation scales in the photosphere. The role of this phenomenon in the evolution of the solar magnetic field is unknown.

- The discovery that the damping of solar atmospheric waves driven by convection cannot account for the energy(3) required to heat the corona and drive the solar wind.

The correlation between the level of intensity of coronal phenomena observed in other stars (which, like the sun, have convective envelopes) and their stellar rotation rate has reinforced the conclusion (drawn from solar observations) that magnetic effects underlie many of the active phenomena observed in stellar atmospheres.

- The discovery that, when viewed on a fine scale, the solar magnetic field is subdivided into individual flux tubes with field strengths exceeding 1000 gauss.

The physical size of these fundamental magnetic flux elements is smaller than can be resolved by any present telescope(4). The cause of this phenomenon is unknown. More recently, rocket observations have shown that the transition region contains very fine scale structures which are highly dynamic. These structures, which appear to be fundamental to atmospheric heating, are beyond the resolving power of present instruments.

- The demonstration that the large-scale solar-magnetic field is organized into two distinct types of structures: magnetically closed regions, in which hot plasma magnetically confined in loops largely generates the x-ray corona; and magnetically open regions, the so-called "coronal holes," which are the source of high speed streams in the solar wind (Figure 6-1a)(5).
- The confirmation of the evidence (provided initially by 17th century observations) that the sunspot cycle and associated active phenomena were largely absent for a period of 70 years in the 17th century.

This episode is known as the Maunder Minimum(2a, 6). We now know that such interruptions, along with periods of heightened activity, occur quasi-periodically and that there is a correlation between the general level of solar activity and the occurrence(6) of climatic changes on the Earth (Figure 6-1b). The cause of this modulation of the solar activity level is unknown. Recently, SMM observations have shown that the solar luminosity varies as a function of sunspot activity, and with the solar cycle; the implications of these variations for the Earth's climate are not known.

- The recognition, as a result of observations of hard x-rays, gamma rays, and energetic neutrons, that the energy released during the impulsive phase of a solar flare is initially largely, or entirely, contained in nonthermal particles accelerated during magnetic-reconnection processes in the coronal field(8).
- The discovery that the ejection of large clouds of gas called coronal mass transients(5) can occur in association with some flares.
- The discovery by SMM that the elemental abundances in x-ray emitting flare plasma vary during the flare event.

SMM observations have shown that both protons and electrons are accelerated promptly

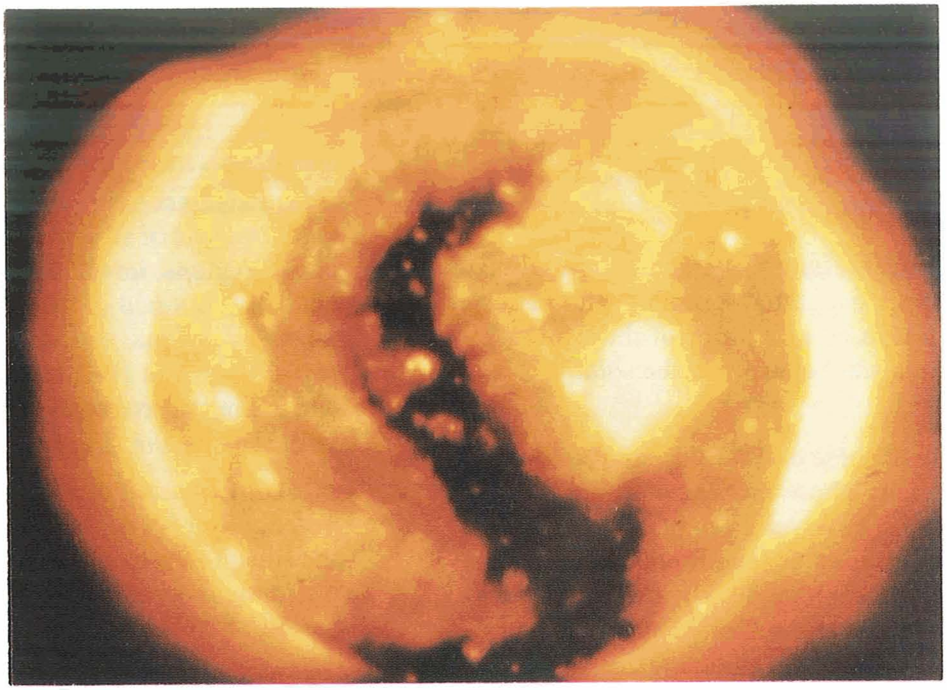

Figure 6-1a. X-ray Photograph of the Sun

This photo, taken August 21, 1973, with the American Science and Engineering instrument on Skylab, shows large coronal loop structures and many small bright points thought to be loops that are too small to be resolved. A large coronal hole extending from the north pole across the equator is plainly visible.

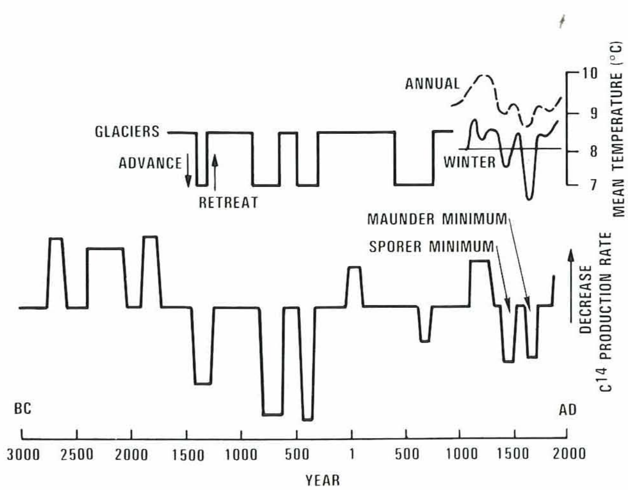

Figure 6-1b. Apparent Correlation of Solar Activity and Climate. The lower curve, based on tree-ring data, represents the rate of production of carbon-14 by cosmic ray bombardment of the upper atmosphere. This production varies inversely with solar activity. Plotted above are measures of mean European climate: the advance and retreat of alpine glaciers, historical inferences of mean annual temperature, and the recorded severity of northern European winters. The temporal coincidence of low solar activity and cool European climate suggests a casual connection between long-term solar behavior and climate, although other data indicate a more complex relationship.

during a flare. The electron acceleration mechanism demonstrates fine time structure (on a millisecond scale), and evidence for the production of bursts of beamed electrons which transport flare energy by propagating along coronal magnetic flux tubes.

A comprehensive review of the current status of solar physics is contained in the three volume set "The Physics of the Sun,"(8) which is recommended to those who wish to pursue in depth any of the specific topics mentioned above.

The profound impact of these and other discoveries on our appreciation of the complexity and diversity of solar phenomena has led to the maturing of solar physics as a scientific discipline. This new maturity has allowed solar physicists to formulate a much more precise theoretical and observational strategy for their discipline(9).

6.2.2 Solar Physics—Expected Accomplishments Through 1995 and a Plan for Continuing Advances into the 21st Century

The current plans for the study of the physics of the sun from space are, at best, modest, even considering initiatives of other countries. There is now no cohesive plan for extending the accomplishments of previous and current major space missions, such as Skylab, P78-1, SMM, and Hinotori. Without such a (US) plan, the vital unsolved scientific problems in solar physics will not be properly attacked. The only near-term programs which can investigate a limited number of solar physics problems are the Solar A and SOHO missions, rocket flights, and the Max 91 balloon program. We therefore first briefly review from a broad perspective the major scientific problems which we believe will remain unsolved by 1995.

Several reports which were written over the last 10 years have identified most of the questions that can be studied from the Earth and space. These are:

1) The Colgate Reports (*Space Plasma Physics: The Study of Solar System Plasmas,* 1978, and *The Physics of the Sun*, 1985).
2) The Kennel Report (*Solar-System Space Physics in the 1980's: A Research Strategy,* 1980).
3) *Solar-Terrestrial Research in the 1980's* (1981).
4) The Nature of Solar Physics: Chapter III of *"Challenges to Astronomy and Astrophysics: Working Documents of the Astronomy Survey Committee"*(1983).
5) *National Solar-Terrestrial Research Program* (1984).
6) *A Strategy for the Explorer Program for Solar and Space Physics* (1984).
7) *An Implementation Plan for Priorities in Solar-System Space Physics* (1985).
8) *The Advanced Solar Observatory* (Executive Summary, 1986).
9) "Solar and Space Physics" (*Space Science in the Twenty-First Century: Imperatives for the Decades 1995-2015,* 1988).

The consensus from all the studies identify the following set of broad scientific objectives:

- Structure and dynamics of the solar interior which includes problems of the magnetic cycle and the coupled dynamics of the convective envelope
- Structure and dynamics of the solar atmosphere and solar activity, including the development of active regions and flare and post-flare phenomena
- Coronal dynamics and coupling to the interplanetary medium, including the origin of the solar wind
- Solar-terrestrial relations which go beyond basic solar physics and consider the coupling of solar energy (both radiative and particulate) to Earth.

Table 6-2 lists the basic problems presented by these objectives and the tools required for attacking them. Column 5 lists the near-term missions which can make modest advances to 1995. Column 6 indicates the required space flight capabilities for the vital extension of studies of the sun. The missions listed are described in more detail below.

6.3 Problems and Objectives

6.3.1 A Scientific Strategy for "Pure" Solar Physics

The report of the Solar Physics Working Group of the Astronomy Survey Committee[9] has recommended three themes or areas of concentration as potentially the most productive for solar physics over the next decade. These three themes (Table 6-3) are: (1) development of observational techniques capable of probing the interior structure, dynamics, and composition of the sun; (2) study of the "active phenomena" such as flares, sunspots, the activity cycle, the chromosphere, the corona, and the solar wind, which are a consequence of solar magnetic variability; and (3) study of the role of the sun in shaping the three-dimensional structure and dynamics of the heliosphere. The last two themes will have important implications for our understanding of the Earth's space environment and climate[10]. We can formulate a coherent scientific program which addresses these themes as a series of seven

Table 6-2. Major Scientific Problems in Solar Physics

1. Objective	2. Area	3. Problem	4. Tools for Solution	5. Approved	6. Proposed
Structure and Dynamics of the Solar Interior	Interior dynamics	a) What is the rotation profile of the Solar Interior? b) Are there residual effects from possible primordial abundance inhomogeneities in the young sun? c) What is the temperature of the solar core?	Observation of the sun's radial and non-radial oscillations (a,b,c)	SO[illegible]	GDI:HRTC
			Theory and modeling (a,b,c)	—	
			Observation of the Solar Neutrino Spectrum (b,c)	Galliur	
			Determination of the Solar Quadrupole Moment (a,b)	SOHO	Solar Probe
	Dynamics of the convective envelope	a) What role do convection and circulation play in the convective transport of energy in the envelope?	Extremely high sensitivity measures of velocity and rotation (a,b)	SOHO	OSL
		b) How does large scale circulation operate on sun and what are its effects?	High precision measurements of the brightness pattern of the solar surfaces (a,b)		OSL
			Theory and computer modeling (a,b)	—	GDI:HRTC
	Magnetic cycle	a) What is the origin of the solar magnetic field, and of its secular variation?	Observations of the non-radial oscillations of the sun to deduce the structure of the convection zone (a)	SOHO	GDI:HRTC
		b) What are the dynamics and energetics of sunspots and other manifestations of emerging flux?	Synoptic observations of solar magnetic field with modest resolution, velocity, and magnetic field observations of polar regions of sun (a,b,c)	SOHO	GDI:HRTC
		c) How rapidly and in what way do coronal fields evolve and dissipate?	ATM data analysis; coordinated synoptic x-ray/XUV and magnetograph data with adequate time resolution (minutes to hours?) (b,c)	Solar-A	HRTC Heliosphere
			Highly resolved magnetograms and EUV and optical data; theory plus time-resolved magnetograms, optical data (including velocities) (c)		OSL
Atmospheric Structure and Active Phenomena	Atmospheric structure and dynamics	a) What is the velocity field in the transition zone and corona? b) What is the role of magnetic fields in heating? c) Are time-dependent ionization effects important in the dynamically varying quiet sun? d) What is the relative role of magnetic dissipation and wave propagation in heating the chromosphere and corona? e) What is the role of spcules in the exchange of mass between the chromosphere and corona? f) What is the fine scale structure and dynamical behavior of the magnetic field?	XUV and ultraviolet spectroscopy with high spatial and spectral resolution	Solar-A	OSL, HRTC
			Moderate time resolution; x-ray, XUV, radio imagery (a,b,c,d)		
			High-resolution magnetograph, visual, ultraviolet, XUV, x-ray data; ATM data analysis (b,f,e)	Solar-A	OSL, HRTC
			XUV and ultraviolet line ratio observations, theory (c)	0	OSL, HRTC
			High resolution measurements of the photospheric velocity field (d)		OSL
	Active regions	a) What is the nature of sunspots: why are sunspots and flare knots stable? b) What is the role of coronal bright points in the emergence or magnetic flux? c) How are coronal loops heated, how do they exchange mass with the chromosphere? Are they chemically homogenous? d) What is the role of prominences and coronal condensations in the energetics of the corona?	Theoretical studies of basic dynamical effects in sunspot structure; observational studies of wave fluxes from sunspots; very highly resolved magnetograms and optical data: theory (a,b,c,d)		OSL
			High-resolution visible, ultraviolet, XUV x-ray, and radio imaging, and spectrophotometry (a,b,c,d)	Solar-A	OSL, HRTC
			Synoptic studies at visible, radio, ultraviolet, and soft x-ray ranges (c,d)	Solar-A	HTRC
			Highest resolution EUV, visible, and radiobservations; theoretical studies (a,b,c)	SOHO	HTRC
	Flares and transients	a) How does stored energy build up in coronal fields and how is it released? b) What is the site of the impulsive energy release in flares, what are the details of reconnection and particle acceleration processes? c) How is the energy released in flares transported to other parts of the atmosphere and dissipated? d) What is the mechanism which triggers coronal transients? e) How does chemical and isotopic fractionation in flares occur?	Temporal and spatial magnetograph data with concurrent soft x-ray and radio imagery, theoretical dynamical studies (a,b,c)	Solar-A	HRTC, HEIC, P/OF
			Hard x-ray imaging and spectroscopy; gamma-ray and energetic beam impact-point observations, high-resolution microwave mappings; fast meter decameter radioheligraph (FeXXI, white light flares) (b,d)	Solar-A	HRTC, HEIC, P/OF HRTC, HEIC, P/OF
			High-resolution visible, ultraviolet, XUV, x-ray and centimeter-wave imaging and spectrophotometry (c)		OSL, HRTC, P/OF

Table 6-2. Major Scientific Problems in Solar Physics (Continued)

1. Objective	2. Area	3. Problem	4. Tools for Solution	5. Approved	6. Proposed
			Solar cosmic-ray observations with good elemental and isotopic resolution; gamma ray spectra with high resolution and sensitivity; XUV and soft x-ray abundance studies (b, e)	Solar-A	Heliosphere, Solar Probe
The Corona and the Interplanetary Medium	Coronal structure and dynamics	a) What are the processes responsible for heating and mass transport in the quiet corona and coronal holes? b) What role do coronal transients play in the energy and mass balance of the corona and solar wind? c) How does chemical fractionation in the corona arise and what is its relationship to abundance anomalies in flares and in the solar wind?	Imaging and spectroscopy in visible ultraviolet, XUV, x-rays; high-resolution magnetic fields; fast meter-decameter radio heliography (a,b,c)	SOHO, Solar-A	OSL, HRTC, P/OF
			Radio polarization observations, white light coronagraph polarization studies (a,b)	SOHO	P/OF
			Development and coordination of the theoretical modeling with empirical models; observation of coronal temperature and density structure with white-light and Lyman-α coronagraphs; ultraviolet, XUV and soft x-ray line profiles (a,b,c)	SOHO, Solar-A	HRTC, P/OF
	The solar wind	a) What is the structure and composition of the solar wind over coronal holes, over light bright points, and over active regions? b) How is the solar wind accelerated? c) What mechanisms are responsible for the observed variations in the composition and temperature of the solar wind? d) What is the angular momentum of the solar wind and what is its role in the evolution of the sun? e) What is the structure of the solar wind and interplanetary medium at mid and high heliocentric latitudes?	Complete coordinated data on corona and solar wind parameters; theory and computer modeling; extend interplanetary data closer to sun and out of the ecliptic (a,b)	SOHO	HRTC, P/OF
			Well-calibrated observations of angular momentum of solar wind, ultimately out of the ecliptic (d)	Ulysses	P/OF, Heliosphere Solar Probe
			Out-of-the-ecliptic measurements (e)	Ulysses	Solar Probe
			Better composition measurements of solar wind; theory of ionic diffusion in transition zone and separation in solar wind (c)	0	Heliosphere, Solar Probe
	Solar terrestrial relations	a) What mechanisms are responsible for the very long-term variations in solar activity which cause phenomena such as the Maunder Minimum b) Are there indicators which allow the prediction of long-term (activity cycle) variations in the trends and short-term (flares, transients) events on the sun which affect conditions on the earth? c) What is the best way to monitor the level of solar activity and the structure of the interplanetary medium in relation to ionospheric, magnetospheric and atmospheric physics? d) What are the mechanisms which are responsible for short-term and long-term variations in the solar constant? e) How do variations on the sun control the structure of the interplanetary medium?	Observation of the sun's and nonradial oscillations (a,b,d)	SOHO	HRTC
			Proxy studies of the level of solar activity over very long periods, studies of solar like stars (a)	—	
			Studies of the structure and evolution of the corona coupled with studies of the non-radial oscillations (e)	SOHO	HRTC, P/OF
			Synoptic observations of solar ultraviolet emission, upper atmosphere, magnetospheric studies (c)	UARS, EOS	SVO, Janus
			Improved atmospheric modeling (c)	—	
			Continue the coordination and statistical study of solar, interplanetary, and terrestrial conditions (c,e)	—	SVO, Janus SVO, Janus
			Precision synoptic observation of total solar luminosity (d)	UARS, EOS	SVO, Janus

— Theory
0 None planned

Key:

SOHO	Solar Heliospheric Observatory
ASO	Advanced Solar Observatory
P/OF	Pinhole Occulter Facility (Part of ASO)
HRTC	High Resolution Telescope Cluster (Part of ASO)
HEIC	High Energy Instrument Cluster (Part of ASO)
GDI	Global Dynamic Instruments (Part of ASO)
OSL	Orbiting Solar Laboratory
UARS	Upper Atmosphere Research Satellite
SVO	Solar Variability Observatory
Janus	A proposed Solar Terrestrial Observatory
Gallium	Search for low energy solar neutrinos with a gallium based detector
EOS	Earth Observation System

fundamental questions, which present an overview of the theoretical and observational issues which should be the focus of solar research over the next decade.

1. What are the fundamental properties of the solar core (where energy is generated) and the radiative interior (through which energy is transported to the sun's outer layers)? In particular, what is the sun's internal rotation rate, chemical composition, and temperature distribution, and what is the detailed process of nuclear energy generation and energy transport? How do these properties relate to current theories of stellar evolution?
2. What is the magnetohydrodynamic structure of the solar convection zone, and what is the

Table 6-3. "Pure" Solar Physics—
Scientific Objectives

Themes from the report of the Solar Physics Working Group of the Astronomy Survey Committee
Structure and dynamics of the solar interior
Rotation profile, energy source
Nature of solar convection
Origin of solar magnetism
Atmospheric structure and active phenomena
Velocity fields, magnetic and acoustic dissipation, fine structure
Active regions (origin, heating, evolution)
Flares and transients (energy accumulation, trigger mechanism; high energy particle acceleration)
Recurrent phenomena (e.g., sun spots)
Corona and interplanetary medium
Structure and dynamics
Origin of solar wind

role of the convective scales observed on the sun, the granulation, the supergranulation, and the large-scale circulation, in transporting energy from the solar interior to the solar surface? Can a generalized theory of stellar convection in the presence of rotation and magnetic fields be developed which describes the structure of the sun's convective zone and predicts the observed convective scales?

3. What physical mechanisms drive the solar magnetic field and activity cycle, what resulting variations in the solar radiative and particulate output follow on various time-scales, and what is the effect of this variability on the Earth's atmosphere, ionosphere, and magnetosphere? What causes the long-term variations in the solar magnetic and activity cycles, such as occurred during the Maunder Minimum? How do these phenomena relate to activity and variability on other stars?
4. What processes, involving small scale velocity and magnetic fields and various wave modes, determine the thermal structure and dynamics of the solar photosphere, chromosphere, and corona, and what are the implications of such processes for stellar atmospheres in general?
5. What are the basic plasma-physics processes responsible for metastable energy storage, magnetic reconnection, particle acceleration, and energy deposition in solar flares and related nonthermal phenomena? What are the implications of these for other high energy processes in the Universe?
6. What are the large-scale structure and plasma dynamics of the solar corona, including the processes involved in heating various coronal structures and initiating the solar wind? What are the implications for stellar coronae and winds other astrophysical flows? What is the origin of coronal transients?
7. What are the implications of coronal structure for the three-dimensional structure and dynamics of the heliosphere and what are its implications for cosmic ray modulation and for the modulation of planetary atmospheres, ionospheres, and magnetospheres, including those of Earth?

6.3.2 Solar-Terrestrial Physics

The solar output at ultraviolet and x-ray wavelength has profound effects on the upper atmosphere of the earth (Table 6-4). The chemistry of the atmosphere, the energy budget, and perhaps the dynamics of the stratosphere and lower mesosphere, are solely determined by the incoming UV radiation in the $120 \text{ mm} < \lambda < 300$ nm band, while XUV radiation at $15 < \lambda < 100$ nm determines the energy budget of the thermosphere. X-rays are absorbed or scattered in many layers. The solar cycle variations of the thermosphere are governed by the strongly variable solar XUV radiation. Ozone concentration in the stratosphere is dependent on the solar UV radiation between 180 and 300 nm. It has been

Table 6-4. Identification of Physical
Mechanisms Long-Term
Variability

Problems in Solar-Terrestrial Physics
• **Radiative coupling sun-upper earth atmosphere**
Energy, chemistry and dynamics of stratosphere, mesosphere and thermosphere
• **Coupling between solar wind and magnetosphere**
Reconnection processes
Trigger of magnetic substorms
Particle acceleration, plasmoid ejection
Aurora
Large scale electric field systems
• **Sun-earth weather**
Confirmation that apparent statistical correlations have a physical basis
Identification of physical mechanisms responsible for any correlations verified

estimated that a decrease of 5% of the solar radiation at 250 nm results in an ozone column density change of approximately 2.5%.

Solar cycle induced ozone column density variations are therefore comparable to long periodic variations caused by chemicals released from the surface of the Earth. It is impossible to distinguish between the two effects as long as no precise knowledge exists of the sun's 11-year variability at the critical UV wavelengths. The list below shows the required precision and accuracy of the solar UV spectral irradiance over a solar cycle, a solar rotation, and short intervals, such as flare-induced variations.

	0.1.5 - 15 nm Soft X-rays		15 - 100 nm XUV		180 - 300 nm EUV	
Time	Precision	Accuracy	Precision	Accuracy	Precision	Accuracy
11 Years	10%	20%	5%	10%	<1%	<5%
25 Days	5%	20%	2.5%	10%	<0.5%	<5%
~Minutes	5%	20%	2.5%	10%	<0.5%	<5%

Short-term solar UV variability (days to months) is caused in first order approximation by excess radiation of plages (UV intensity is modulated by the evolution of the plages, and by their passage across the solar disk as a result of the solar rotation). However, there are strong indications that a so-called third component may significantly contribute to the 11-year cycle variation. This third component may consist of small, isolated chromospheric brightnings distributed over the whole solar disk, or a uniform variability of chromospheric temperature. It is obvious that total solar irradiance measurements cannot distinguish between the two- or three-component model, however, the understanding of the solar cycle and its underlying magnetic variations requires a resolution of this problem.

Therefore, a need exists for synoptic observations of the sun over a solar cycle at all UV wavelengths with good spatial resolution (~1 arc second) and appropriate time resolution (~1 day).

The correlation of atmospheric parameters with the solar cycle, taking into account quasi biannual oscillations which were first found by Labitzke[11], has survived severe statistical tests. Furthermore, it has now also been detected in tropopause weather patterns. Although it is at present only a statistical correlation, solar terrestrial physics has the mandate to find a plausible mechanism which couples either solar constant variations, solar UV flux variations or changes in solar corpuscular emission with tropospheric weather patterns.

6.3.3 Solar/Stellar Relationships

One of the major discoveries of the first comprehensive x-ray observatory, the Einstein Observatory, was that stellar coronae are common phenomena, arising naturally in cool stars as a result of the convective transport of energy in the outer envelopes of these stars, and by a variety of mechanisms in other circumstances, such as close binary pairs. Another major discovery of Einstein was that the quasar phenomenon, like the coronal phenomena, is essentially a result of the generation of very high temperature plasmas (10^7 to 10^9 K) by nonthermal processes, which involve the acceleration of particles to very high energy. It is a fact that the extensive community of astronomers which has formed to study coronal and other nonthermal phenomena in stars has come essentially from solar-physics. Clearly, the comparative study of solar and stellar coronal phenomena, and the relationship of coronal parameters to basic stellar parameters (mass, age, surface temperature, rotation rate, etc.) is essential if an understanding of coronal phenomena, and activity cycles in stars is to be achieved. The objectives of comparative solar/stellar studies are summarized in Table 6-5.

Table 6-5. Solar Stellar Properties

Objectives of Solar/Stellar Studies
Scaling of coronal properties (temperature, density, filling factor) with fundamental stellar parameters
Mass
Surface temperature
Surface gravity
Rotation rate
Properties of stellar activity cycles, scaling of activity cycle characteristics with stellar parameters
Comparative properties of stellar winds and the solar wind
Comparative properties of solar and stellar flares
Flares in main sequence and giant stars
Flares in "pathological stars," i.e., flare stars, close binaries

6.4 Present Program

The present program is summarized in Table 6-6. The data base from previous years is an important resource. The near-term programs, and the presently operating missions (SMM, rockets) can address specific problems, however they do not provide the very high resolution (~0.1 arcsecond) necessary for many critical problems.

Table 6-6. Present Programs—Solar Physics

Resources and Operating/Near-Term Missions
Data base from previous missions - Skylab, OSO series, P78-1
Operating:
SMM Continue acquiring data base for > one 11-year cycle
Rockets ~5 year now desirable to increase
Near-Term (<1995):
SolarA --some advances for all objectives but a small explorer--high energy very limited
SOHO some advances for all objectives but flares
Rockets—5 year desirable to increase
MAX91—some significant advances possible but limited by short duration
Conclusion: Existing program is inadequate!

6.5 Potential Implementation Modes

In order to accomplish the broad objectives of solar physics over the next 25, or so, years a number of modes (Table 6-7) are considered. Following is a list of these modes with a brief statement of the advantages derived through the use of these modes.

1. Rockets and balloons: These modes are the most responsive in terms of the time from concept to data analysis. They are most supportive of the "graduate student" approach to developing scientific research, and have proven an excellent means for the development of new instrument and investigation techniques.
2. Small Explorer missions: This mode may be used to support relatively small groups of diagnostic instruments and innovative instruments for longer time periods.
3. Moderate Explorer missions: This mode of implementation begins to allow for the development of more comprehensive instrument packages. Single large instruments or multiple instruments may be included which provide high time and spatial resolution of specific solar structures.
4. Major missions: The major missions employ large single or multiple instruments, which are expected (with periodic servicing) to remain in orbit and operation for at least 10 years. The instruments for these major missions may be changed and upgraded over the life of mission.
5. Shuttle attached payloads: This mode of implementation is most beneficial for the employment of large instruments which do not require long duration (less than 10 days) missions. This mode is also useful for the testing of new instruments and the development of investigation techniques. Launch schedule uncertainties are a major problem.
6. Space station attached payloads: This mode of implementation (although presently uncertain) may be most attractive for the deployment of multiple large observatory instruments. The space station should allow for the accommodation of instruments requiring large footprints, and will provide power, thermal control, data handling, commanding, and other resources. In addition the ability to recalibrate, repair, and upgrade these instruments will significantly enhance the scientific return. Problems which could occur include contamination, light scattering from station structures, and disturbances caused by shuttle dockings and other space station operations.

6.5.1 Modeling and Theory Programs

In order to maintain a balanced program in solar physics, it is essential that the observational programs be complemented with a significant modeling and theory component. Such programs should include both a "pure theory" emphasis independent of flight programs, and more concrete efforts aimed at directly understanding and predicting observational results. The development of solar models and theories must be infused with experimental results, and experiments should be developed with an eye toward verifying the models and theories.

6.5.2 Data Analysis Campaign

To allow effective utilization of the wealth of data which has been obtained from prior

Table 6-7. Potential Implementation Modes

Modes	Time (Concept to Implementation)	Cost*	Instrument Modality
Rockets and ballons	∿1 year	(1)	Quick response, graduate student support
Small explorers	∿5 years	(2)	Single or multiple small instruments
Explorers	∿10 years	(3)	Large or multiple instruments
Moderate missions	∿15 years	(3)	Large or multiple instruments with "strap-ons"
Major missions	∿20 years	(4)	Large instrument, long duration, upgrades
Shuttle attached	∿8 years	(2)	Large instruments, development, calibration
Space station attached	∿10 years	(3)	Large instruments, long duration, upgrades
Lagrangian point orbits	∿15 years	(4)	Multiple instruments
Lunar basing	∿20 years	(4)	Large instruments, long duration
<1 AU platforms	∿20 years	(4)	Multiple instruments, steroscopic observations
"Event emphasis" data analysis missions	∿1 year	(1)	Quick response, to include models and theory

*Cost
(1) ≤$1M (3) ≤$500M
(2) ≤$100M (4) >$500M

missions such as Skylab, P78-1, SMM and Hinotori, a series of data analysis campaigns is most appropriate. These campaigns might be implemented at the rate of one or two per year with the objective of addressing specific solar features through the review and analysis of data compiled from prior missions. Teams of investigators could be selected to work on "special emphasis" scientific programs using existing data resources. Teams would include not only experimentalists, but also specialists in the modeling and theories relating to the features under study. We expect that the state of knowledge in solar physics could be significantly enhanced by the implementation and proper management of such an effort.

6.5.3 Observational Modes

A broad attack on the basic solar plysics problem after 1995 must first consider the possible available platforms and the unique capabilities and limitations of each platform. These are (with foreign collaboration encouraged):

- Earth orbiting free flyers: Precise pointing, long-term undisturbed observations—full wavelength coverage
- Space station utilization: Heavy payloads with modest SS impact—availability of manned support
- Space shuttle: Flights of opportunity—verification in space of key instrument advances, calibration, and quick-return before long-term placement in space
- Suborbital flights: Same advantages as space shuttle and in addition low in cost and good for training of young scientists
- Solar orbiting-free flyer (~1 AU): Stereoscopic observations
- Lunar basing or Lagrangian point: No atmospheric disturbances—weight and volume limitations, satisfactory, if manned base support
- Inner planet observations: $1/r^2$ advantages for angular resolution, stereoscopic observations, low energy neutron spectroscopy
- Heliosynchronous orbit (approximately 0.1 AU): $1/r^2$ advantage for angular resolution, stereoscopic observations, low energy neutron spectroscopy

- Near-sun orbit: $1/r^2$ advantage for angular resolution, stereoscopic and in-situ observations, low energy neutron spectroscopy
- Solar probe (one short mission): $1/r^2$ advantage for angular resolution, stereoscopic and in-situ observations, low energy neutron spectroscopy

Note: $1/r^2$ advantage refers to the improvement in resolution and sensitivity of solar structures achieved by placing an observing platform closer to the sun than 1 AU.

A few remarks regarding Shuttle Attached Payloads are appropriate. After the Challenger accident, most of the Spacelab payloads in the space physics discipline were cancelled. Seven years of development were discarded. This resulted not only in a tremendous loss of future science which could have been obtained from multiple flights of scheduled instruments, but also in a crisis of confidence between NASA and the impacted sectors of the scientific community. This trend must be reversed. Sustained efforts must be made to find flight opportunities for existing instruments or, if this is not possible, other means to carry out the investigations. However, there exists a *class of instruments which must be carried by the shuttle* because of the need for long-term (approximately solar cycle) measurements which require periodic reflights and calibrations between flights. Some of these experiments are scheduled on the ATLAS mission which must be flown periodically over the next 10 years simultaneously with the UARS satellite for calibration purposes.

6.6 Solar Physics Strategy

6.6.1 Introduction

We have identified three major goals of "pure" solar physics:

1. Understanding the phenomenology displayed by the sun, including the activity cycle, the generation of the corona and the solar wind, the acceleration of energetic particles in flares, and the structure and dynamics of the heliosphere.
2. Understanding the variability of the radiative and particulate output of the sun, and its effect on planetary ionospheres, atmospheres and magnetospheres, particulary those of the earth.
3. Understanding solar phenomena, such as particle acceleration, coronal heating and solar wind generation, in relation to similar phenomena in other astrophysical settings.

Each of the objectives will require specialized programs and specific measurements to address the outstanding problems. A basic solar physics strategy to obtain the necessary observations is presented in Table 6-8. The objectives of the missions listed in the table are summarized in Table 6-9. The study of solar phenomenology, for example, requires very high spatial and spectra resolution to achieve a physical model of the small scale structures which control the flow of mass and energy in the atmosphere. Also required are in-situ measurements of the microscopic conditions in the heliosphere, and remote observations of the global properties of the heliosphere.

The study of solar-terrestrial phenomena requires the precise measurement of solar outputs and their variation, and the understanding of the origins of this variation. Finally, direct measurement of coronal and other nonthermal phenomena on other stars is essential to an understanding of the sun in an astrophysical context. In the following discussion, we have specified the fundamental measurements which must be made, and commented on a strategy or strategies by which such measurements can be achieved.

6.6.2 Suggested Missions

We briefly describe each of the major goals identified above, and discuss missions by which these goals can be achieved.

The Solar Activity Cycle and the Magnetic Field

The thermodynamic structure and dynamics of the solar atmosphere are determined by the interaction of magnetic field and plasma on a very small scale. The objective of the Orbiting Solar Laboratory (OSL) is to provide the angular resolution, sensitivity, and stability to permit study of the fundamental interactions of solar surface wave and flow fields with the magnetic

Table 6-8. Solar Strategy

Strategy
• Orbital Solar Laboratory (OSL) is the top priority for solar physics
• Because Solar Physics has multiple objectives (solar phenomena, the heliosphere, solar terrestrial relations, astrophysical phenomena observable on the sun), several different types of solar measurements, and hence several types of solar observing capability, are required. The missions which are required are summarized below:
– Very high resolution instruments with diagnostic capability: OSL, High Resolution Telescope Cluster (HRTC), High Energy Instrument Cluster (HEIC) including the Pinhole/Occulter Facility (P/OF)
– Very high precision instruments for the study of the solar output and its variability: Solar Variability Observatory (SVO), Janus
– Multiple in situ and remote sensing (for global structure) instruments to study the heliosphere: Solar Probe, "Heliosphere"
– Comparative solar/stellar observations of coronal, cycles, etc.

Table 6-9. Summary of Solar Missions

Solar Physics	SOHO/ Cluster	OSL	HRTC	HEIC	Solar Probe Heliosphere	SVO Janus	Scout/ Explorer
Convection zone	✓						
Photosphere/chromosphere		✓		✓			
Transition reg./corona/ solar wind	✓		✓	✓			
Solar wind/heliosphere	✓		✓		✓		
Solar Terrestrial Relations							
Solar output/variability						✓	
Terrestrial response						✓	
Solar Stellar							
Stellar and solar corona, flares, winds							✓

Nature of Missions	Scout	Expl	Mod	Maj	Shuttle Attached	Space Station Attached
OSL			✓			
HRTC:P/OF			✓			✓
HEIC:P/OF			✓			✓
Solar probe				✓		
"Heliosphere"	✓		✓			
SVO/Janus			✓		✓	✓
Solar/stellar	✓	✓				

field at the scale of 100 km. OSL is complementary to Solar and Heliospheric Observatory (SOHO), Solar-A, the NOAA x-ray imaging monitor and the ground-based project in the primary objective of understanding the solar cycle.

OSL is the highest priority mission in the discipline of solar physics. The priority has been recently reaffirmed by the Space and Earth Science Advisory Committee. The future strategy for solar physics and the ability of the discipline to contribute with fundamental understanding to the "input" side of solar-terrestrial studies depend upon the early implementation of this keystone mission. The capabilities of OSL are summarized in Table 6-10.

Table 6-10. Orbiting Solar Laboratory (OSL)

OSL Major Facilities	
Photospheric magnetic and velocity field (visible light)	
High spatial, high spectral resolution	
0.1 arcsecond	$\lambda/\Delta\lambda$ >500,000
Long time sequences	~days (SS orbit)
Chromospheric and transition zone spectroscopy (UV)	
Spatial resolution	0.5 arcsecond
Spectral resolution	$\lambda/\Delta\lambda$ ~30,000
Coronal imaging and spectroscopy (XUV, x-ray)	
Spatial resolution	0.5 arcsecond
Spectral resolution	$\lambda/\Delta\lambda \gtrsim 100$

A thorough understanding of the convective conditions in the sun which underlie the solar activity cycle will require the study of the solar oscillations, which will be one of the objectives of the SOHO mission.

High-Energy Investigations of Solar Phenomena

The most striking accomplishments of the SMM and Hinotori missions have been the realization that the very efficient acceleration of individual electrons and ions to relativistic energies on short time scales is a fundamental property of solar flares and probably of other cosmic plasmas. An understanding of this phenomenon would have ramifications in the broadest astrophysical context. The specific parameters and observations needed are as follows:

- The species and maximum energies of accelerated particles. This information can be derived from measuring the spectra of x-rays, gamma rays, and high-energy neutrons with high time and energy resolution.
- The physical properties of the acceleration region, such as its location and composition. This requires precise imaging of hard x-ray and gamma ray emissions to MeV energies and measurement of gamma-ray spectra with the highest energy resolution.
- The geometry of the accelerator. This requires determining the angular distribution of secondary neutral emissions from individual flares and can be accomplished by high resolution imaging, stereoscopic observations, Doppler shifts of gamma-ray lines, and polarization measurements of bremsstrahlung and nuclear emissions.

By focusing strong effort on one of the most fundamental problems of solar flare physics, one can expect to advance to an understanding of how the flare itself is triggered and how the energy released is distributed in numerous other forms and transported throughout the solar atmosphere.

The properties of the high energy instruments necessary to address these objectives are summarized in Table 6-11. Some of the instruments required are high resolution gamma-ray and neutron spectrometers which can be accommodated on a platform with only modest pointing capabilities. This group of instruments is referred to as the High Energy Facility (HEF). The hard x-ray and gamma-ray imaging instruments will make use of coded aperature imaging techniques, and will be part of the Pinhole/Occulter Facility (P/OF) described below. Together, the high energy instruments are referred to as the High Energy Instrument Cluster (HEIC).

Table 6-11. High Energy Instrument Cluster [Thrust through 2002 (next solar maximum after 1991)]

Major objective—advance aggressively to an understanding of high energy particle acceleration
Parameters and measurements
Accelerated species and maximum energy of each species
High energy and high time resolution spectra of x-rays, γ-rays, neutrons
Acceleration region (e.g., location, composition...)
Imaging x-rays and γ-rays to 1 arc second
High energy resolution spectra
Geometry of accelerator
Angular distribution of emissions from:
High resolution imaging, stereoscopic observations
Nuclear line Doppler shifts and polarization
Bremsstrahlung polarization

High Resolution Studies of Chromospheric and Coronal Structure and Dynamics

The upper chromosphere, transition region, corona, and corona/solar wind interface span temperatures from 5 x 10^4 K to 10^7 K. During flares, plasma with quasi-thermal temperatures as high as 10^8 K are generated. These plasmas are confined to very small structures, especially in the early phase of flares. A cluster of high resolution hard x-ray, soft x-ray, x-ray ultraviolet (XUV) and EUV telescopes able to carry out diagnostic observations on spatial scales of ~50-100 km (~0.1 arc second) is necessary to address fundamental issues such as:

- Coronal heating of active regions loops
- Mass transport between coronal and chromospheric structures
- Generation of the solar wind

- Acceleration, transport, and thermalization of energetic particles.

Many of the required instruments can be incorporated in a High Resolution Telescope Cluster (HRTC), which can accommodate the required high resolution soft x-ray, XUV, and EUV telescopes. The measurement of the faint structures in the corona/solar wind inteface will require occulted telescopes, which are most effectively incorporated into the P/OF mentioned above. The hard x-ray imaging observations will require the use of coded aperature techniques, which can be accommodated on P/OF.

The Advanced Solar Observatory

Many of the problems pertaining to high energy phenomena on the sun will require the combined power of the OSL, and instruments described in the discussions of High Energy Investigations and High Resolution Studies. This set of instruments will have the highest resolution and sensitivity of any of the instruments envisioned in this report, and are collectively referred to as the Advanced Solar Observatory (ASO). The ASO instruments are most effectively packaged into four ensembles: the OSL, a Pinhole/Occulter Facility which makes use of Fourier transform imaging techniques and occulted coronal telescopes which use a remote (~50 meters) occulter/mask; a HEF which incorporates high energy gamma-ray and neutron spectrometers; and a HRTC. The properties of these ensembles are summarized in Table 6-12. The OSL is already NASA's highest priority for a moderate mission. The other ASO instrument ensembles (HEF, P/OF, HRTC) could be deployed on the manned space station, on a co-orbiting platform, or on two moderate size spacecraft, such as that planned for the OSL. Perhaps initial deployment on the space station, and later extended deployment on another platform is the most logical approach. The HRTC telescopes, the OSL, and the HEIC [including hard x-ray and gamma-ray imaging (i.e., P/OF)] must be capable of being operated as a single observatory, as described in the Advanced Solar Observatory SWG Report(12). Instruments for the HEF are described in a recent publication(13).

Heliospheric Studies

The solar corona (where the solar wind is formed) remains one of the most ill-observed regions of the solar-terrestrial environment, in spite of the fact that a total eclipse can make some of it directly visible to the naked eye. Some of the observational problems can be eased by new missions that emphasize (a) remote sensing; (b) stereoscopic viewing, to permit tomographic reconstruction of the corona's three-dimensional geometry; and (c) direct in-situ measurements of conditions in the heliosphere. These needs can be met by deep-space observatories (heliosynchronous, Lagrangian-point, or planet-based) carrying relatively low-resolution solar imaging instruments such as (a) white-light and UV coronal imagers, (b) soft x-ray telescopes, (c) low-frequency radio receivers and solar energetic particle and solar-wind particle measuring instruments, and by a probe of heliospheric conditions as close to the sun as possible.

The extended solar atmosphere (the heliosphere) is extensive and highly structured. To understand the dynamics of the heliosphere, it is necessary to observe the physical processes occurring on microscopic and macroscopic (meters to kilometers) scales, as well as the global structure and dynamics (i.e., coronal mass ejections). Accordingly, both in-situ missions such as a Solar Probe, capable of approaching the sun to within 4 solar radii, and a complex of remote sensing platforms which allow stereoscopic imaging of the far corona (e.g., ISPM) as well as in-situ sampling of heliospheric conditions both in and above (or below) the ecliptic are essential. We call the later complex of platforms "heliosphere"; heliosphere might include a "heliosynchronous orbiter" and an "interstellar probe" which could travel beyond 100 AU from the sun.

The Solar Probe would carry out the first in-situ exploration of the solar corona, penetrating to a height of about 4 solar radii above the photosphere. This innermost region of the solar wind approaches the "temperature maximum" of the corona, where the heating is the strongest, and remains one of the most inaccessible frontiers of

Table 6-12. ASO Instrument Ensembles

Instrument	Spectral Range	Aperture	Resolving Power: Angular (arc sec)	Resolving Power: Spectral (g) (E/ΔE)	Resolving Power: Temporal (sec)	Field of View (arc min)
High Resolution Telescope Cluster (HRTC)						
Soft X-Ray Telescopes[a]	1.5 - 170 Å	40 cm	0.15/0.4[f]	10,000	0.01	3.5' x 3.5'/12' x 12'[1]
XUV Telescopes[b]	150 - 310 Å	40 cm	0.1/0.4[f]	20,000	0.01	3.5' x 3.5'/12' x 12'[1]
EUV Telescope	550 - 1100 Å	40 cm	0.1/0.4[f]	30,000	0.1	3.5' x 3.5'/12' x 12'[1]
Gamma Ray Imaging Detector	2 - 1000 keV	60 cm	1.6	10	0.001	full sun
X-Ray Flare Spectrometer	1.5 - 25Å	40 cm	1.0	10,000	0.01	full sun
Global Dynamics Instrumentation[c] (GDI)	3500 - 11,000 Å	50 cm	0.5/5[c]	100,000[c]	1.0	full sun
Ultraviolet Telescope	1175 - 1700 Å	60 cm	0.1	30,000	0.1	3.5' x 3.5'
High Energy Facility (HEF)						
Gamma Ray Line Spectrometers[e]	10 keV-10 MeV	30 cm/60 cm	—	400/20	1/0.25	full sun
High Energy Gamma Ray Spectrometer	10 MeV-100 MeV	100 cm	—	5	0.001	full sun
High Energy Neutron Spectrometer	10 MeV 1000 MeV	100 cm	—	5	0.001	full sun
Low Frequency Radio Spectrograph	1 20 MHz	30,000	90	200	1	full sun
Pinhole/Occulter Facility (P/OF)						
Coded Aperture Imager	2-70 keV	100 cm	4.0	10	0.001	full sun
Fourier Transform Imager	2 1000 keV	100 cm	0.2	10	0.001	full sun
White Light Coronagraph	1100 11,000 Å	50 cm	1.0	5,000	1.0	full sun
EUV Coronagraph	300-1700 Å	50 cm	1.0	20,000	0.1	full sun
Orbiting Solar Laboratory (OSL)						
Optical Telescope	2000-1700 Å	100 cm	0.1	100,000	0.1	1.3' x 1.3'/3' x 3
Ultraviolet Telescope	1175 - 1700 Å	30 cm	0.5	30,000	0.1	4' x 4'

a Our strawman configuration envisions two soft x ray telescopes with spectral coverage 1.5 - 2.5 Å and 10 - 170 Å
b Our strawman configuration envisions three XUV telescopes with spectral coverage 150 - 180 Å, and 280 - 310 Å
c The Global Dynamics Package includes four small telescopes
d Possible long term future upgrade for the OSL ultraviolet telescope
e Entries refer to high resolution and high sensitivity spectrometers respectively
f Entries refer to high resolution and wide field modes respectively
g Figure refers to highest resolution mode. Other modes may have lower resolution

corona, where the heating is the strongest, and remains one of the most inaccessible frontiers of the heliosphere. The Solar Probe should carry instrumentation for the measurement of the magnetic field and of the populations of thermal and energetic particles, including neutrals; it should also carry out spectrophotometry of the outer corona by viewing outwards from the sun.

Solar-Terrestrial Physics

The sun/heliosphere/Earth system forms a tightly coupled physical system, which must be studied as a single entity with simultaneous observations of the solar radiative and particulate outputs, the transport of the solar particulate output to the Earth, and the response of the Earth's magnetosphere, ionosphere and atmosphere to these inputs. An attempt will be made to measure the solar EUV ($120 < \lambda < 400$ nm) with the required precision and accuracy from the UARS satellite and the shuttle "Atlas" missions starting in 1991. However, because of the limited lifetime of UV photometers, *new instruments must be flown no later than 1995.* We propose a "Solar Variability Observatory" to carry out these important observations (Table 6-13). Any platform which can be pointed toward the sun is suited. The *space station* must be *favored* because its instruments can be exchanged

Table 6-13. Solar Variability Observatory Solar Component

	SMM	UARS	EOS	Space Station
Spectral irradiance $120 < \lambda < 400$ nm		XX 91-	XXX 95-	
Spectral irradiance 15kλk120 nm				XXX 95-
Spectral irradiance Soft x-rays				XXX 95-
Imaging 120kλk400 nm				XXX 95-
Imaging 15kλk120 nm				XXX 95-
Imaging Soft x-rays				XXX 95-
Total solar const.	X	XX 91-	XXX 95-	

X Ongoing XX Future Effort XXX New Initiative periodically. It is necessary to *add high precision photometers for the XUV regime* because no efforts are ongoing at the time being. Table 6-13 lists planned solar irradiance measurements, and the components of a future Solar Variability Observatory.

To carry out a comprehensive measurement of the variation of the solar irradiance and particle output and of the response of the Earth's ionosphere, magnetosphere, and atmosphere to these variations, we purpose a two-spacecraft mission which we call Janus.

The Janus mission is named after the Roman god of gates and doorways who, having two faces, looked both ahead and behind. The name is appropriate because the primary spacecraft is to be located at the Lagrangian libration point L1 between the sun and the Earth and is equipped with both sun viewing and earthward looking instruments.

The objective of the Janus mission is the study of solar-terrestrial relationships from the global perspective. It utilizes both in-situ and remote sensing techniques to observe the solar input and global response of the earth's atmosphere. Absolute calibration of Janus instruments will be maintained by periodic comparison measurements on the space shuttle or space station, and calibrating the Earth's global photometry by using stars as calibration standards. This will produce a record of Earth's luminosity which should be extremely accurate and which can be reviewed in 100 years to detect long-term trends. Two spacecraft provide the necessary observing perspective, Janus L1 at the libration point and Janus Polar in high (ca. 18 hour) circular polar orbit.

The purpose of Janus L1 is to observe the solar electromagnetic, particle and magnetic field input to the Earth vicinity, and to carry remote sensing instruments to image the sunlit hemisphere of the Earth to obtain precise albedo measurements. The solar instruments are tailored to the particular solar-terrestrial task.

The Janus Polar satellite is intended to provide global remote sensing coverage of the polar regions, the day-night terminators and the dark side of the earth. In the course of a year Janus Polar will acquire detailed coverage of seasonal effects such as auroras, distribution of trace gases, ozone distribution, etc., in both hemispheres. The satellite will be equipped with appropriate in-situ particle and field sensors to trace the magnetospheric effects of the incident streams observed by Janus L1.

Although the Janus mission deserves careful and thorough definition, the two spacecraft will need to include instruments of the following types:

Janus L1
- Solar viewing:
  - Solar constant monitor
  - UV irradiance monitor
  - Soft x-ray photometers
  - Soft x-ray or XUV imager for coronal structure data
  - Wide angle coronagraph for mass ejection data
- Earth viewing:
  - Geocoronal imagers
- In-situ particle and field monitors

Janus Polar
- Earth viewing:
  - Auroral imager
  - Ozone imager
- In-situ particle and field monitors

The Janus concept is described in Table 6-14 and Figure 6-3.

Comparative Solar/Stellar Observations

A logical approach to the comparative study of coronal phenomena on the sun, and on other

Table 6-14. Solar-Terrestrial Mission "Janus"

Janus Concept
1. Earth as a "sun": Earth irradiance photometry
Global composition and physical properties of the earth
Global ozone and other minor constituants of the upper atmosphere
Global cloud coverage, thunderstorms
Global albedo of the solid earth
2. Earth as a planet: Earth imaging
Structure, dynamics of the atmosphere
Global hydrology oceans and atmosphere
Ocean temperature, ice caps, desertification
3. Earth as a "long-term variable star": Search for global changes

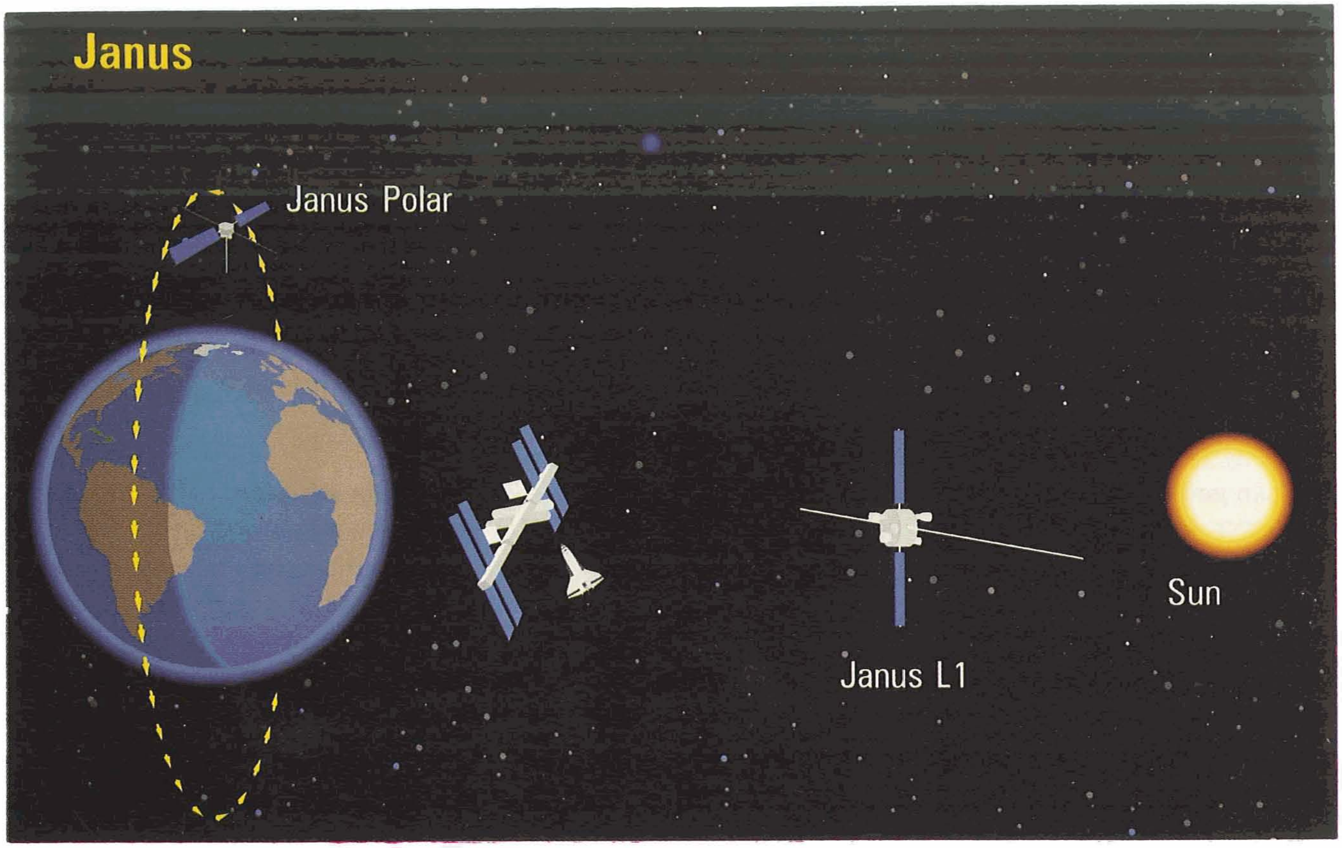

Figure 6-3. The Janus Mission

stars, is the development of a small dedicated spacecraft which can complement IUE (and the projected Lyman mission) by observing both the sun and nearby stars at XUV, EUV, and soft x-ray wavelengths.

6.7 Advanced Instrument Development

Most solar space instrumentation planned for flight on long-duration platforms in the next decade is based on technical developments which are 10 to 20 years old. Ten years ago, NASA substantially curtailed large-scale support of future technology. Examples of areas urgently in need of development funds are two-dimensional detector arrays for UV, x-ray, and gamma-ray wavelengths, and new optical technologies. Instruments now under construction for missions such as SOHO, may, therefore, carry considerable risk. Instruments planned for future missions, such as OSL, need a catch-up effort of uncertain outcome. Twenty years ago several industrial efforts were supported with research funds which resulted in useful products. Most of these efforts have disappeared. For example, images obtained by the Naval Research Laboratory (NRL) XUV monitor on board Skylab (flown 15 years ago), which were based on technology developed 20 years ago, have never been superceded. This is an extremely alarming trend that needs to be rectified by steady, generous support of future technology developments.

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Chapter 7

Report from Space Plasma Science

Panel: D.E. Hastings, Chair; A. Drobot, P.M. Banks, W.W.L. Taylor and H.R. Anderson

7.1 Introduction

The solar-terrestrial environment exhibits many complex charged particle and plasma phenomena. The energy and particles released in solar flares, the dynamic structure of the magnetosphere, the fluctuating terrestrial aurorae, and the convective motions of the ionosphere are different examples of the pervasive influence of plasma processes. Knowledge of the constitutive physical processes underlying these phenomena is important in several ways. First, it allows us to understand in quantitative terms the variety of interrelated, complex processes acting to shape and influence our terrestrial environment. Second, these phenomena also pose fundamental scientific questions relating to the behavior of plasmas under conditions which are different from those which can be created and studied in conventional laboratories. As a consequence, their investigation extends the frontiers of human knowledge, enabling broader physical understanding of plasmas within the context of their general behavior.

Previous chapters discussed the need to investigate space plasma phenomena through many different modes of investigation, including: (1) passive remote observation, (2) passive in-situ observation, (3) initiation of experiments involving active perturbation of natural phenomena, and (4) execution of experiments taking advantage of the different ranges of physical parameters and conditions available in space. Observations of plasma density and drift speed, energetic particle fluxes, and magnetic intensity are examples of studies of space plasmas which are directed towards understanding the natural processes linking the atmosphere, ionosphere, magnetosphere, interplanetary medium, and the outer solar atmosphere. Such studies are essential parts of other disciplines devoted to explaining the myriad of complicated processes found in and above the Earth's atmosphere.

7.1.1 Plasma Experiments

Space plasma science, however, involves more than simply observing and understanding the solar and terrestrial plasma environments. The ionosphere, magnetosphere, and interplanetary space present opportunities for conducting basic plasma experiments outside the confines of the vacuum chamber walls necessary for ground-based investigations. Plasma experiments in space open the way to increasing knowledge of plasma phenomena on new scales of time, space, and frequency and wavelength. In addition, the natural environment offers a variety of ambient conditions that are difficult to replicate in laboratories. Naturally occurring variations in density, flow velocity, magnetic field intensity, temperature, and ion composition can be exploited to conduct fundamental experiments which are essentially impossible to undertake in the confines of the laboratory. These experiments can involve injection of electromagnetic waves, foreign plasma, charged particle beams or other perturbations, and subsequent observation of responses, often at distances of thousands of kilometers. The interpretation of these results in terms of basic plasma processes provides a means of adding to and improving our knowledge of fundamental plasma physics.

7.1.2 Computational Simulations

Owing to the complexity of phenomena, it is prudent to discuss the important role of computational models in space plasma science. Over the past two decades our capability to numerically investigate the behavior of space plasmas has steadily improved. Models and simulations of the 1960s and 1970s evolved as a consequence of attempts to understand particular features of the solar-terrestrial environment; e.g., the composition and thermal structure of the atmosphere and ionosphere, the dynamics of inter-hemispheric plasma interchange, the coupled dynamics of energetic plasma in the magnetosphere and electric fields and currents in the magnetosphere and ionosphere, the interaction of the solar wind with the geomagnetic field, the formation of shocks in the solar wind, the propagation of solar and galactic cosmic rays in the solar wind, and the dynamics of magnetic reconnection, among others. More recently, the ability to study plasmas on a microscopic scale has evolved through the use of various simulation techniques with supercomputers. These codes permit the investigation of various modes of plasma dynamics associated with internal energy and momentum transfer between the plasma constituents and plasma waves. Unfortunately, owing to limitations of computer resources, these studies are often limited in terms of their spatial and temporal resolution. Examples of current codes include computations of two stream instabilities associated with plasma currents, the interactions of high energy radiation belt particles with VLF waves, and the generation of electrostatic waves and plasma turbulence.

Great progress has also been made in computing the conditions associated with plasma experiments conducted in space. Our ability to understand striations in ionized barium clouds has been enormously enhanced by application of computer models. Simulations of the dynamics of electron beams injected into dilute plasma from a space platform have expanded our knowledge of the dynamics of electron beam-natural plasma interactions. Models of the AMPTE gas and plasma comets have enabled us to interpret and guide complicated space experiments towards identification of new processes. For the future, it is clear that experiments in space plasma must involve synergistic participation of experimentalists with theoreticians capable of modeling the anticipated interactions. For such support, a community of theoretical plasma scientists must be present and supported with adequate computer resources and contact with experimental programs.

With this background, we now present the general areas of investigation for space plasma science. These brief discussions complement the active space experiments which have already been suggested in previous chapters to expand knowledge of processes involved in solar-terrestrial science.

7.2 Basic Processes of Space Plasma Science

7.2.1 Wave Generation and Propagation

Waves are a ubiquitous feature of plasma and their study in a broad range of physical conditions is an important goal of plasma science. Indeed, one of the goals of the ground-based plasma fusion research is to eliminate waves, since they are often unstable, unpredictable, and can steal energy otherwise destined to heat the plasma. Waves also carry information through plasmas and knowledge about their means of generation and modes of propagation provides new insight to the various internal processes affecting the overall plasma state. Waves can also transfer energy from one part of a physical system to another.

Understanding the generation and propagation of waves, including electromagnetic and electrostatic modes, in space plasmas is important as a general goal of plasma physics. The ability to make measurements over a variety of scale lengths with differing plasma parameters extends conventional laboratory studies. In the past, space studies have concentrated on explaining in-situ observations of waves in terms of various sources of free energy; i.e., plasma currents, density gradients, the presence of energetic particles, dc electric fields, plasma flow, etc. In the future, it is clear that more detailed investigations should be undertaken, including the direct injection of electromagnetic waves from space platforms, and the use of modulated charged particle beams and plasmas.

7.2.2 Wave Particle Interactions

Wave-charged particle interactions include the microscopic electromagnetic interactions between waves in plasmas and the charged particles which make up the plasma. Wave-particle interactions are one process by which energy and momentum are transported between different regions of plasma systems. Wave-particle interactions are exceptionally rich in their diversity, even for the simplest plasmas. When the added degrees of freedom connected with imbedded magnetic fields and multi-component plasmas are considered, wave-particle interactions are found to be among the most complicated physical processes occurring in any plasma environment.

Studies of wave-particle interactions in space involve observations of the nonlinear evolution of the particle and wave distribution functions arising from the interaction. The knowledge gained from such studies is valuable both for understanding basic plasma physics and, if the conditions are chosen correctly, it will also help in understanding specific processes, for example, those occurring in the magnetosphere and the solar atmosphere.

7.2.3 Charged Particle and Plasma Energization

Charged particles in plasma can be accelerated to high energies through a variety of mechanisms, some of which occur in nature or can be induced in suitably arranged space experiments. These include:

- Particle acceleration through resonance with a quasi-monochromatic wave
- Stochastic acceleration resulting from resonance overlap due to large wave amplitudes or the presence of a finite spectrum of waves
- Acceleration by electric fields which results from changes in macroscopic plasma morphology
- Acceleration by parametric processes, such as beat waves, Brillouin, and Raman scattering. These phenomena are fundamentally nonlinear and extremely complicated.

The understanding of all of these critical phenomena is an important goal for space-plasma science in the next decade.

7.2.4 Chemistry and Active Experiments

The natural space environment can be modified with the introduction of foreign gases and plasma to induce or enhance local processes. This includes changes of the local ion composition, reduction of the local electron density, changes in the charge state of ions, changes in the average energy of the local plasma, its chemical nature, and so forth.

Another possibility is the opportunity to change the energy state of the atmosphere by electromagnetic radiation or by particle beams. The first category includes laser-pumped or radiation-heated local regions which may have been chemically altered through release of suitable materials. Electron beam heating has been done in artificial aurora experiments, and will be attempted in equatorial electron beam experiments. These experiments are valuable in that they allow comparison of theory with experiment and permit identification of new or unexpected interactions.

Chemical releases are often used to modify the charge state of the ionosphere. This permits study of various processes occurring within ionospheric plasma, including production, loss, and transport. It is also a way of creating unstable environments which evolve in interesting and new ways not normally found in the natural environment. The possibility of creating large-scale ionic plasma (positive and negative ions dominate the overall composition) is both interesting and important in that it allows new processes to become dominant in plasma behavior. Such experiments are difficult, if not impossible, to make in terrestrial laboratories.

7.2.5 Particle-Particle Interactions

These processes are generally those that involve collisions. The important consequences are:

- Excitation, ionization, and dissociation of atoms and molecules with consequent radiation and change of plasma density
- Recombination leading to decreased plasma density
- Heat conduction
- Electrical current conduction normal to the magnetic field
- Forcing of winds in the neutral atmosphere through collisional interactions

- Creation of unstable ion velocity distribution functions through charge exchange with energetic neutral particles
- Initiation of unusual ion-neutral reactions through high speed interactions.

Future studies linked to careful measurements of these processes offer a rich reward leading to accurate, detailed models of plasma interactions.

7.2.6 Radiation Processes

This topic is relatively new and involves the detailed study of the production, transport, and absorption of microwave, infrared, and shorter wavelength radiation in dense plasma. The interaction of such radiation with matter involves individual molecules, atoms/ions, or electrons, not collective plasma processes. (Interaction of longer wavelength radiation with plasma is discussed in Section 7.2.1.) Clearly, radiation processes are of fundamental importance in transporting energy through portions of the sun and of the earth's atmosphere. In addition, radiation propagating freely from its source and from optically thick regions is the primary means by which remote sensing is accomplished. The opportunity to study fully coupled electromagnetic radiation with plasma dynamics in the space environment supplements the extensive work done in laboratory plasma on similar problems.

7.2.7 Macroscopic Flow of Plasma

Macroscopic flow of plasma is one of the fundamental processes behind the transport of energy, momentum, magnetic, and electric fields across the magnetopause and through the magnetosphere and ionosphere. The transport of plasmas and particles in space is one of the key processes underlying the behavior of the boundary region between any two regions of contracting plasma. Specific examples are the magnetosphere/ionosphere boundary, as well as the boundary between the artificial environment around a space structure and the ambient space environment. This transport is most likely mediated by instabilities which cause particle scattering in a manner akin to classical particle collisions. This wave-induced transport is still one of the fundamental areas for research in basic plasma physics.

7.2.8 Plasma-Magnetic Field Interactions

Studies of interactions between energetic plasma and magnetic fields are an important direction for the future. Previous work with high-speed barium releases in magnetized space plasma has demonstrated a wealth of complex interactions, including the formation of a diamagnetic cavity, a larger region of electrostatically polarized plasma moving with the source, and an even larger coma of disturbed flow. Similar observations exist in laser plasma experiments.

Using space platforms with suitable resources, investigations of steady-state diamagnetic cavities should be possible. In this situation, the plasma effusion speed from its source can be made larger than the diffusion speed of magnetic field. In this situation, a complex region of low magnetic field is maintained by plasma pressure against the flowing ambient plasma and ambient magnetic field. This is an unstable situation which opens the way to investigation of various types of instabilities. It is likely that these will reveal the presence of many new high beta plasma-magnetic field interactions which depend on various plasma and magnetic field parameters.

Magnetic field interactions, analogous to the solar wind-geomagnetic field coupling, can also be anticipated as the capability to construct and operate large magnets in space evolves. These experiments, involving a variety of plasmas and magnetic field configurations, will have relevance to a wide range of astrophysical situations.

It is also important to note that investigations of the phenomenon of the Critical Ionization Velocity effect are an important part of space/plasma science. This process involves the nonclassical ionization of energetic neutral atoms and molecules as they move through a background magnetized plasma. From laboratory studies, and perhaps some space measurements, it is thought that when the center of mass energy of the neutrals rises above their ionization threshold, there will be a rapid ionization of the neutrals. This process apparently involves energization of the ambient electron gas by plasma waves associated initially with the transformation of a few energetic neutrals to ions. The newly born ions have considerable kinetic energy, and through collective plasma processes, this heats the electrons. When sufficient neutrals are converted to ions, such as might happen through charge exchange, the energy density of the electron gas rises to the point where additional ionization of the neutrals ensues, and a flash ionization of most neutrals occurs.

This process has great significance for models of young solar systems, and comprehensive measurements of the processes involved are essential. To do this it will be necessary to achieve the correct physical scale; i.e., the electron gas must be heated over a sufficiently large scale so that its temperature can rise to the point where impact ionization of the neutrals becomes important to the overall system of interacting gases. Such experiments lie in the future and will require much more extensive supporting resources than have been possible with small free-flying satellites or rockets.

7.2.9 Plasma-Surface Interactions

Processes in the physical contact between plasma and exposed surfaces in space are an important, practical aspect of many advanced scientific and technological space systems. The ability to draw electron current from magnetized space plasma, for example, is an essential feature of plans for power-producing electrodynamic tether systems. Charging of dielectrics in the vicinity of high current beam experiments is similarly an important concern. It is striking to realize that while basic issues of plasma sheaths and current extraction have been known for more than 50 years, we still lack fundamental knowledge of the processes involved, especially at high voltages and currents. Relatively simple experiments, such as measuring the voltage-current collection curves for magnetized plasma, have yet to be done for ranges of parameters when large amplitude plasma waves play an important role.

Much of our present knowledge of plasma sheaths comes from laboratory measurements. In the case of electron current collection, this has imposed severe limitation on the scale of phenomena which can be studied. Because the total number of electrons in a given plasma chamber is limited, measurements of electron current are limited in time and current density to very small values.

In contrast, measurements in space offer a far better situation since it is possible to place the collecting anode in an essentially unbounded medium. This permits application of very high voltages and the formation of very large plasma sheaths; i.e., on the order of 10's of meters or more. The behavior of these sheaths can be carefully documented and, furthermore, they can be perturbed in various ways. For example, waves can be injected, the bias potential of the electrode can be varied, and the neutral gas background can be changed. These and other measurements are an important part of the future of space plasma science in the area of plasma-surface interactions.

7.3 Prospects for Near-Term Plasma Science Experiments in Space

Many of the active experiments performed thus far in space have been intended as either tracers in the magnetosphere or as small-scale perturbations of a local environment. Such experiments have used particle beams, gas and plasma releases, chemical releases, and emission of waves, primarily from the ground. In addition, experiments have been performed that may be viewed as simulations of naturally occurring processes. In many cases these experiments have revealed that the interaction between the perturbing agent and the ambient space environment is more complex than anticipated, and, indeed, requires deeper understanding before active experiments can be used with full confidence as diagnostic techniques. Thus, in recent time the focus of active experiments in space plasmas has shifted somewhat to the investigation of fundamental plasma processes.

In the early 1980s, the space plasma active experiments program was scheduled for flight with a number of NASA missions. Missions which have carried important space plasma experiments included STS-3/OSS-1, Spacelab-1, and Spacelab-2. Prior to the Challenger accident, future programs in space plasma science aboard the space shuttle also included Combined Release and Radiation Effects Satellite (CRRES), Tethered Satellite-1, and several flights of a space plasma laboratory. In the reality of post-Challenger mission scheduling, these flights have been greatly curtailed. The CRRES experiments have been descoped and transferred to an expendable launch vehicle. The Space Plasma Laboratory has been cancelled. Furthermore, it has been explicitly stated that the space shuttle will not be considered for space plasma missions through at least the IOC of the US/International Space Station; i.e., 1997 or later.

As a consequence, during the period 1985-95 progress in space plasma science will certainly be reduced below that planned before the Challenger accident. We foresee that only a limited version of CRRES is likely to fly, that ATLAS will carry a reflight of a Spacelab-1 electron accelerator without the possibility of having remote diagnostics, and that only the TSS-1 mission will attempt a new technology. This is certainly a discouraging prospect to the space-plasma science community and leaves open the possibility that expertise now established in this discipline will be greatly eroded by 1995.

In fact, it is clear that the forthcoming Soviet Active and Apex dual satellite missions will enable the Soviets to undertake a wide variety of important space plasma experiments and to make significant strides in this area of space research. While there is an agreement between NASA and IKI to permit US co-investigators to participate in these Soviet activities, this is not likely to lead to significant US involvement in the development of either the basic instruments of space plasma experiments or in the planning of the actual flight operations unless great efforts are made in the near future.

The NASA suborbital program will continue to support experiments with charged particle beams and VLF wave injection. However, with such platforms there is little opportunity to attempt new experiments such as dusty plasmas, or artificial magnetospheres (terrellas) that require larger platforms and significant energy.

It is clearly the case that the loss of the space shuttle as a supportive platform for space plasma science will put aside the possibility of conducting a wide variety of important, innovative experiments in the forthcoming decade.

As a consequence of these factors, it is important for NASA to adopt a near-term strategy which attempts to extract the maximum possible value from space plasma science experiments currently planned. These include those aboard Atlas-1, TSS-1, and CRRES. Increases of support for these missions, and making adequate provision for satisfactory analysis of the data acquired from these missions, will be essential.

In the same vein, NASA should ensure that the data already collected on its space plasma science experiments are adequately studied. Extensive data obtained on STS-3, SL-1 and SL-2 have remained unanalyzed owing to lack of data analysis funds. Data from various rocket flights are likewise under-analyzed. This situation should be rectified, perhaps by identifying these basic data sets as being among those which should be part of the "missions to data" concept described elsewhere in this report.

7.4 Future Plans

It is convenient to arrange the possible active experiments into the various categories given below.

7.4.1 Large-Scale or Global Modifications of Terrestrial Plasma

This category includes such experiments as alteration of the trapped radiation flux by wave injection to induce precipitation, additions of energetic tracer species to the natural trapped flux, alteration of the ionosphere by dumping electronegative species to produce negative ions, and perturbation of the natural current paths. The Workshop agreed that these experiments would be discussed by the other, relevant panels.

7.4.2 Large-Scale Active Imaging and Tracing

This class of experiments includes radar and laser sounding and chemical releases for tracer purposes. Again, these topics are discussed in other sections of this report.

A special experiment discussed by the space plasma science panel is that of active tomography to make observations of plasma density in the ionosphere and magnetosphere. Active tomography is a multiple satellite experiment in which one satellite, the transmitter, transmits electromagnetic waves and the other satellite, the receiver, receives it with the objective of monitoring the region between the two. In the case of radio waves, this technique can be used to monitor the total plasma content. A radio-transmitting satellite would emit phase correlated signals and the receiver would measure the phase shift and Faraday rotation of the signal. From the signal measurement, the total electron (plasma) content and the magnetic field direction of the spatial region between the two would be detected. In the simplest form, two satellites would be orbiting at some moderate distance (few Earth radii) from the other and make tomographic measurements of magnetospheric regions.

In more complex situations, a cluster of receivers would fly and one common transmitter would be used to produce the signal.

The same principle could be used for electromagnetic waves in the optical domain. A tunable light source—perhaps a laser—would be flown on the satellite and the receiver would observe the optical absorption of the space region between the two satellites.

7.4.3 Three-Dimensional Plasma Experiments

Space vehicles offer the promise of performing three-dimensional experiments in unbounded plasma with varying mixtures of neutral gas. These could be done on a scale size that should make the instrumentation easy to build. In addition, the relevant time scales are microseconds or longer, which are easily measured and recorded. In spite of these advantages, plasma experiments in space have not been easy to perform. The principal reasons for this are that diagnostic instruments are difficult to place accurately, and the space platforms that carry them may be big enough to interfere with the experiment.

Examples of three-dimensional plasma experiments are:

- Wave injection
- Particle beam injection
- Plasma injection
- Dust injection
- Production of wakes
- Terrellas/artificial magnetospheres.

These techniques relate to the processes detailed above.

The general requirement for performing these experiments is to provide one space platform that perturbs or alters the natural plasma and diagnostic detectors that can either be maneuvered into the correct positions or that are deployed in a large array. Furthermore, the diagnostics must be small to minimize perturbations and able to telemeter data at a rapid rate, often high for short periods. The proper positions usually are in relation to the local magnetic field and/or the plasma streaming velocity (negative of orbital velocity). For example, to perform particle beam experiments the diagnostics must be maneuvered along the injected beam, which is along the magnetic field, from a few meters to a few kilometers or more. The positioning accuracy in scanning across the beam must be to a few meters or tens of meters, with measurements to be made out to hundreds of meters away from the beam.

As another example, naturally occurring fast-moving bodies which are in a neutral or a plasma medium create wakes. The phenomena associated with these wakes are rather complex and their modeling is particularly difficult. However, relatively simple experiments can be performed on orbiting bodies which simulate the action of the naturally occurring phenomena. Such simulation experiments can be performed in low-Earth orbit. A larger body which creates the wake should be used, and at least one diagnostic spacecraft which has accurate positioning should be used for diagnostic three-dimensional mapping. It is possible to use parts of already planned spacecraft to act as the solid body. Another possibility, conceived more than a decade ago, would be to attach an electrically active tether from the shuttle to a large, conducting echo-like (early US passive communications satellite) balloon.

Comparable requirements must be met in performing other types of experiments. Some experiments of this sort can be done with separating payloads on sounding rockets, and these have the great advantages of ready access to space and low cost. With small satellites it appears difficult to perform experiments that require relative positioning of two bodies over an extended period of time. Some terrella experiments can probably be performed with a single orbiting body having sensors attached.

However, if NASA is going to pursue active plasma and other experiments, a significant investment in facilities is required. Much of this has been recognized for some time and studied before, but is perhaps worth restating in terms of the space station or astronaut-tended platform. The perturbing mechanism should be on the major platform, which can provide significant power when needed. Specially designed diagnostic instruments should be operated on:

- Carefully designed fixed positions on the main platform. Remote sensing at close range may be carefully considered.
- The servicing crane or equivalent. [This is the decendent of the remote manipulator system (RMS)]. This will afford accurate positioning within limited range.
- On one or more maneuverable subsatellites such as the OMV, as suggested by MSFC. This was once studied by GSFC as the Solar-Terrestrial Subsatellite.
- There may be use for multiprobes or the equivalent. The geometry of the perturber is critical. For example, if one is studying wakes or surface interactions, a simple shape is important to make analysis tractable. Particle and injection depends critically on the magnetic field.

Active experiments, balanced with computer models and simulations, can also provide information on plasma transport mechanisms. The first class of experiments includes pulsed plasma beam or contactor experiments where a dense plasma cloud is released into the ambient medium. The plasma cloud expands and distorts in response to its internal diamagnetic structure as well as the external flow field. This expansion sheds light on the fundamental plasma physics of high beta plasma clouds, such as occur in the magnetotail, as well as the nature of the transport process when the cloud is diluted. Such experiments are conceptually similar to those already underway in ground-based laboratories, with an important exception. By using pulses of sufficient density and duration, it is possible to create steady-state diamagnetic plasma regions near the source. Information about the various processes acting in such an unusual plasma configuration is an important step towards understanding a new regime of plasma physics.

Another class of active experiments includes pulsed particle beam experiments where specific instability wave modes are excited. These can be studied for their influence on the particle transport if the pulsed beam is combined with plasma pulses described above.

Finally, using charged particle beams, it is possible to study the propagation of charged particle bunches in magnetized plasma. Motions across magnetic fields have been studied in the context of laser-ionized channels and there are various results from laboratory and theoretical studies which indicate the need for space experiments. With respect to the motions of electron pulses parallel to magnetic fields, there is an urgent need to understand the collective processes affecting such propagation. In general, such a pulse can propagate only when the injected electron density is less than the ambient ion density. In this situation, it is predicted that a potential well will confine the energetic electrons, permitting the well to propagate away from the source at a speed determined by various ambient plasma and injected electron densities and energies. Experiments of such propagation are difficult to make in the laboratory, but can be done relatively easily in space.

7.5 Conclusions

The use of space as a medium for undertaking space-plasma science offers exciting new possibilities for plasma physics as well as other branches of solar-terrestrial science. This new and innovative work should be explored to the fullest extent possible in the coming years. Nevertheless, the loss of the space shuttle as a platform for conducting exciting, new space plasma experiments is a severe blow and the US space plasma physics community must survive until platforms with sufficient energy, and other resources are again available. In the meantime, the Soviet programs, even with joint participation, will most likely bring about a significant shift of leadership in this field. The Soviets are reaping benefits from 15 years of intensive study and planning undertaken now by US scientists and their associated international collaborators. While it is certainly valuable for the US active space science community to participate with the Soviets, this situation may not be advantageous to maintaining a position of research leadership.

To help overcome these difficulties, it is recommended that NASA make strong efforts to fully study existing data from already completed space plasma science missions and experiments. This may involve further funding of the groups who originally conducted the experiments and might be part of a new initiative related to "missions to data."

For those missions which are now scheduled, examination of their science goals and level of support is warranted. These missions, including Atlas-1, TSS-1 and CRRES, will be the sources of data which must carry the space plasma science community through a most difficult period. Supplementing these experiments, and the experiment teams, will come at far less cost than those expenses which accrue to entirely new missions.

The suborbital (rocket) program is an important means for nurturing progress in the field of space plasma science. To maintain research momentum in this field, it will be necessary to provide more flight opportunities than have been available in the past.

In looking to the period after 1995, it appears that a combination of astronaut-tended vehicles and free-flyers can be used for various important experiments and observations. Astronaut-tended platforms, for example, can be used in many active plasma and charged beam experiments. Likewise, the space station will enable entirely new types of experiments requiring substantial electrical power, remote observation sites, and perhaps even small, tethered payloads.

Chapter 8

Major Themes in the Future of Solar-Terrestrial Science

Chapters 3 through 7 have presented results from the individual discipline groups participating in the Workshop. Viewed collectively, there are certain common themes which deserve recognition and further discussion.

8.1 The Evolution of the Concept of the Solar-Terrestrial Observatory

The Solar-Terrestrial Observatory (STO) was conceived in the early 1980s as a response of the solar-terrestrial research community to the possibilities of attached payloads on the space station. Three different experimental activities were incorporated into the facility: observations of the sun, observations of the Earth's atmosphere, and apparatus to conduct active electron beam experiments in the ionosphere. Following extended discussion at the Workshop, it appears that panel members believe the STO was less a product of specific, synergistic science requirements than a pragmatic reaction to the possibility of reflying a suite of space shuttle instruments on the space station. There was little debate about the capability of the individual observing instruments to provide important, new information about the sun and the Earth's atmosphere, or that the electron accelerator and plasma diagnostic equipment would well serve the needs of space plasma sciences. The point was made that there is no obvious need for these instruments to be flown on the space station as part of an integrated payload. Thus, the concept of the STO has undergone an evolution which recognizes that the individual science goals of the STO are largely independent. This means that the respective scientific disciplines can evaluate the specific science objectives of the STO within the context of their own set of priorities for achieving adequate space observations capabilities.

8.2 Global Imaging of Earth and Sun

A remarkable product of the workshop was the universal support for developing technology and space-based capabilities for multispectral imaging of the sun and Earth. With respect to the solar-terrestrial relations, a case was made for obtaining simultaneous, long-term, low-resolution, multispectral images of the sun and Earth. Such a dual observation program, it was argued, would provide a sensitive means of measuring radiative input to the Earth, and the Earth response. The value of viewing Earth in terms of disk averaged measures of spectral radiance was thought by some members to be sufficiently high to justify further, in-depth study by groups of experts concerned with solar-terrestrial relations.

Other concepts of remote imaging of Earth were proposed. The capability to image global atmospheric, ionospheric, and magnetospheric phenomena was thought to hold considerable promise for understanding global processes. Specific phenomena to be studied in this way included gravity waves in the mesosphere, the dynamics of the plasmasphere, simultaneous views of both auroral ovals, and the flow field of high latitude plasma convection.

8.3 Missions for Data Analysis

All groups of the workshop expressed a desire to develop a means for focusing research activities on data acquired from past space missions. In addition to the practical difficulties associated with retrieving old data from archives, the Workshop members felt that NASA, as an institution, is not inclined to give value to such non-space flight activities. However, the members clearly believe that there is much to be learned from revisiting archived and unprocessed data. In particular, the emergence of powerful processors and the availability of unifying theoretical models makes it likely that important relationships of solar-terrestrial science can be discovered from already existing data sets.

In order to give such analysis activities a higher standing, it was proposed that special data analysis activities be solicited and managed along the lines of regular satellite missions; i.e., that there be an Announcement of Opportunity, proposals submitted, and peer evaluation. Investigators could compete for participation in the projects and budget time and resources in a manner consistent with what is done with actual flight projects. In addition, once underway there should be a responsible NASA field center with a staff which would include a project manager, supporting experts, and supporting facilities. In this way selected investigators could work as a team to try to resolve specific questions judged (in advance) to be both meritorious and, with some finite probability, soluble with a given data set.

Further study of this concept is clearly warranted. It may well be that it can apply in some sense to future solar-terrestrial missions where broader participation than just the originally selected flight team is justified on the basis of the growth of capability and needs in the overall science community.

8.4 New Space Missions

Each discipline has proposed its own ideas about possible future space missions. In the relatively short time available for the Workshop, little effort has been spent to explore the commonalities of the proposed missions or to determine any realistic priorities among the large number suggested. Nevertheless, there is an important point underlying the presentations of need for new missions: without new data from space observations and experiments, solar-terrestrial sciences will increasingly run the risk of having theory and modeling outpace fundamental knowledge of the solar-terrestrial system. This is an uncomfortable state of affairs which represents pendulum-like oscillation from too little theoretical activity to the point where there may be too little real information to discern the alternatives inevitably offered by theoretical analysis.

Associated with this problem is that of having to decide when enough is known about a given physical process or environment. Scientific observations can be made with increasing spatial, spectral and temporal resolution if sufficient funds are made available. How can one decide when the scientific return from a field has reached the point where the costs outweigh the potential gains? How can one value that which is not known?

In the case of solar-terrestrial science, the desire has been to identify and model general or global processes on the sun and Earth. As long as new experiments continue to provide data which conflicts substantially with theoretical predictions, and as long as we lack fundamental information known from other fields to be of great importance to understanding complex situations, there will be justification for supporting new scientific endeavors in this discipline. The long-term value of understanding the sun and the Earth are beyond dispute.

8.5 New Vantage Points for Viewing Earth and Sun

An interesting aspect of the Workshop has been the interest of the members in identifying new vantage points for observing solar and terrestrial phenomena. As discussed in Chapter 6, the Solar Physics group introduced the idea of having a dual viewing spacecraft looking at the Earth and sun from the L1 libration point. The Magnetospheric Science group mentioned the possibility of using the moon as a site for remote imaging of the magnetosphere and for measuring parameters of the magnetospheric tail. These all deserve careful consideration.

Related to this is the need of magnetospheric sciences to make fundamental measurements simultaneously at a number of locations within the tail of the magnetosphere. The current state of affairs with respect to magnetic reconnection in the tail is that present and future experimental data will be inadequate for judging between competing models of the reconnection process. It is thought that an approach similar to that of the ESA Cluster mission will be needed to make progress on this important question.

8.6 International Collaboration

International collaboration was discussed and affirmed as an important ingredient of solar-terrestrial science. While at one time the United States was the clear leader in initiating new flight programs, this will no longer be the case in the future. The planned ESA SOHO, Ulysses, Cluster and European Polar Platform missions, as well as the Soviet Interball and IKI-Equator missions are visible evidence for a change towards much more balanced (or dominant) international contributions. In order to assure that the US solar-terrestrial community has access to the data from these projects, it is important that the US stimulate collaboration among the international institutions, as it has in the past. Members of the Workshop heard that some aspects of the international relations are of concern to the international partners, largely because of the lack of action towards the development of a formal means of establishing scientific liaison at the space agency level. Recognizing that many different factors are involved in developing such ties, the Workshop urges that prudent steps be taken to insure that such uncertainties do not jeopardize the position or possibilities of US scientists to participate in international solar-terrestrial science ventures.

8.7 Explorer-Class Satellites

There is a clear need by all disciplines for using Explorer-class satellites to achieve important scientific goals in the future beyond the current missions now being planned. Without such flexible platforms, the vitality of the disciplines will be seriously eroded.

8.8 Space Shuttle Missions

According to information given to the Workshop, only two shuttle missions remain that have important experiments associated with the Space Physics Division. These are the ATLAS-1 mission with a reflight of some Spacelab-1 experiments, and the Tethered Satellite-1 mission, with its complement of US and Italian experiments designed to measure electrodynamics associated with a conducting tether and satellite system. It is now the policy of OSSA to assign future shuttle missions, at least through 1994, to other divisions and principally the Materials and Life Sciences Divisions.

The Workshop was of the opinion that this represents an important loss to all of the disciplines in solar-terrestrial science and that the Space Physics Division should continue to press the issue of acquiring new missions in support of the science programs of the divisions. In particular, Space Plasma Sciences has been badly damaged by this decision since its experiments make heavy use of the high power afforded by the shuttle and the crew resources. Other disciplines had their examples of valid need for the shuttle.

The Workshop urges the Space Physics Division to continue to prepare its science and programmatic arguments for shuttle missions for the 1991-1994 period, recognizing that there may be significant changes in the shuttle manifest over the next several years. Furthermore, the Division should look towards the future when the extended-duration Orbiter will be available for enhanced science missions.

As a group, it is also fair to mention that Workshop participants who have participated in shuttle science missions are appalled at the high costs of using this vehicle. In the long run, and if these costs continue to escalate as they have in the past 5 years, it may well be that the expense of using the shuttle will prevent its use as a scientific platform. NASA should make every possible attempt to resolve this serious problem.

8.9 Space Station and Other Astronaut-Associated Platforms

Attached payloads on the space station will be important to solar-terrestrial sciences. For solar physics, the space station represents a unique means for making long-term, highly calibrated measurements of solar irradiance. The opportunity to exchange detectors frequently is an important aspect of this work.

Space Plasma Science was also able to make strong claim to space station resources for its program of active plasma experiments. The combination of frequent transportation, local crew support, high electrical power, substantial instrument areas, and the possibility of having a large baseline between active sources and diagnostic instruments was judged to be of great importance.

It should be noted, however, that there was considerable concern about the possibility of instrument contamination from the space station. In addition, the low inclination orbit rules out many science possibilities for ionospheric and magnetospheric investigations on the manned base. The occasionally visited polar platform, however, was thought to provide important opportunities for these disciplines.

The concept of using externally attached payloads on small, astronaut-tended platforms or pressurized modules received strong support from all disciplines. In making this judgment, the members of the Workshop noted that the projected once per 6 months visitation schedule was adequate for most purposes, and the local environment of such facilities would be, in all probability, less contaminated than that of the permanently manned space station. This arises as a consequence of the less frequent reboost periods, the passive boom stabilization systems, and the smaller overall leak rate of the single pressurized module. Efforts to determine the practicability of using tended stations should be pursued by the Space Physics Division as a less expensive, earlier available platform than the permanently manned space station.

8.10 Theory and Modeling

The members of the Workshop strongly agree with NASA's support for theory and modeling. Such fundamental activities provide important direction to understanding the myriad of processes acting in the solar-terrestrial environment and help guide new experimental programs. Ultimately, most experimental knowledge gained from space observations and experiments should be understood within the framework of fundamental physics and chemistry. At the present time, the disciplines are far from such a state of unified understanding. Continued involvement of individuals and groups who deal with theoretical issues and computer modeling, along with those who deal with analysis of data and those who make space observations and experiments, should be an important part of the balance of the solar-terrestrial research program.

8.11 New Instrument Development

The Workshop notes that the Space Physics Division currently has no ongoing budget line for the development of new instruments. Such funds have proven valuable to investigations supported in other Divisions and members of the Workshop give their strong support to the Division Director in his attempts to create such a program.

Chapter 9

Recommendations for the Future

The Solar-Terrestrial Sciences Workshop has explored four major areas of concern to solar-terrestrial science:

1. The current level of understanding which will be gained from execution of NASA's current program of space and ground-based measurements
2. The major scientific questions facing solar-terrestrial science in the next decade
3. The identification and evaluation of the space capabilities available for undertaking new investigative programs
4. The development of strategy for identifying and implementing keystone programs, taking into account practical constraints and other factors.

Looking across the discipline reports given previously, it is possible to find common threads that can contribute to the development of NASA's programmatic strategy for the solar-terrestrial sciences. These are outlined in the following paragraphs.

9.1 Scientific Balance

We strongly recommend to NASA that progress in solar-terrestrial science must be seen and implemented in terms of the achievement of scientific goals rather than simply in the establishment of new space missions. While there is an important need to gather new information from space using new and improved sensors, platforms, and orbits, the measurement programs themselves must be undertaken within the context of a larger, balanced scientific undertaking. Theory, simulation, analysis of previously gathered data, and adequate analysis of new data must all be viewed in a harmonious balance. As any one phase of this balance is altered, so the overall science program is affected.

In the past, solar-terrestrial programs have focused on well-conceived flight programs. Unfortunately, as mission costs have risen, funds available for pre- and post-flight scientific analyses have been reduced, co-investigator participation has been reduced or eliminated, and instruments and spacecraft have been lost. This process leads to an inevitable fragmentation of the originally planned science objectives and organization. In these cases, some means must be found to absorb the changes while assuring the best possible science output measured in terms of the complete scientific program, not just the viability of the spacecraft portion of the undertaking.

9.2 The Value of Previously Gathered Information

We strongly recommend that in the next decade efforts must be made to integrate previously gathered scientific information into solar-terrestrial science studies. This workshop, composed largely of individuals who have participated in space experiments and observations, strongly recommends the concept of "missions to data." There is a virtually unanimous opinion that NASA's emphasis upon new missions, and inability to adequately fund long-term data analysis, retards the development of solar-terrestrial science. Older data, when interpreted in terms of new models and simulations, has the potential to provide new insights and knowledge important to all solar-terrestrial disciplines.

9.3 Imaging

We strongly recommend that steps be taken to advance capabilities and opportunities to view solar-terrestrial phenomena as two-dimensional images in many different wavelength bands. The capabilities for this have evolved to the point where most disciplines feel important, new scientific information can result from new missions using these type of detectors. Sun- and Earth-looking platforms can begin to assess phenomena in terms of global scale effects and relationships.

9.4 The Impact of Space Stations and Related Platforms

We recommend that the Space Physics Division take advantage of the opportunities for solar-terrestrial science associated with use of space stations, the space shuttle, and other vehicles which are related to the presence of humans in space. Depending upon different factors, each discipline sees these platforms in different ways. Those disciplines using active experiments find value to the presently conceived US/International Space Station in terms of its availability of energy, high peak power, commodious externally attached payload space, and the opportunity to have occasional human presence. However, the limitations of the space station orbit, the restrictions of field of view, and the possible presence of a deleterious environment are of concern to others, and especially those who use sensitive telescopes and other detectors.

We also recommend that the Space Physics Division pursue the use of potential resources offered by astronaut-tended space platforms, including both pressurized modules and open, unpressurized vehicles. In some cases, such platforms are to be preferred over the more dynamic accommodations associated with the space station. The attractive features include the possibility of semiannual visits, a capability for instrument/detector exchange and repair, and the absence of the inevitable outgassing associated with permanent human presence.

For many active experiments the space shuttle is still regarded as an important means to implement solar-terrestrial scientific studies. However, it is clear that there are many negative aspects to using the shuttle as a scientific platform. Many of these lie in the difficulties of dealing with the NSTS system and its stringent requirements for safety and mission planning rather than with shuttle performance on-orbit. We recommend that planning begin again for use of the shuttle when it becomes available for solar-terrestrial scientific research.

9.5 Vitality and Relevance

The results of this workshop demonstrate that solar-terrestrial science has lost none of its vigor or relevancy: Maturity has brought appreciation of the need for the fundamental information provided by study of the sun-earth system. Earth and its relationship to the space environment must remain as an important part of scientific study for the decades yet to come.

9.6 Future Studies

The present study has touched upon many different complex issues. It is recommended that further, in-depth studies follow soon. Each discipline has developed its own new ideas about what can be done in the decades ahead, and these deserve greater exposure to the solar-terrestrial scientific community. We recommend that this report be given wide distribution to solar-terrestrial scientists and that it be used as a means for sparking ideas and plans for future steps to be taken by NASA in pursuit of its mission to explore and understand the solar-terrestrial system.

Appendix I

Solar-Terrestrial Strategy Panel Workshop

Agenda

September 8, 1988

Monday, September 12

8:45 a.m.	Welcome, local arrangements information and opening comments — Peter Banks, Stanford
9:00 a.m.	Reflections on the TFSUSS experience — Peter Banks, Stanford
9:30 a.m.	Charge to the STSPW — Stanley Shawhan, Director, Space Physics Division, NASA Headquarters
10:30 a.m.	Mid-morning break
10:45 a.m.	Space station and its resources for science in the '90s — John Bartoe, Office of the Space Station, NASA Headquarters
12:15 p.m.	Lunch
1:15 p.m.	Small attached payloads for space station — Vernon Jones, Code ES NASA Headquarters
2:15 p.m.	The Industrial Space Facility — Tom Bonner, Space Industries, Inc.
3:15 p.m.	Mid-afternoon break
3:30 p.m.	Group discussion of the Workshop Report and activities of the Discipline Panels — Peter Banks, Stanford University
4:15 p.m.	Discipline group meetings
5:45 p.m.	Hello Again Reception, Stanford Faculty Club

Tuesday, September 13

9:00 a.m.	Report on Solar-Terrestrial Observatory activities — Bill Roberts, NASA Marshall Space Flight Center
10:00 a.m.	Report on ESA ST activities — George Haskell, ESA*
10:30 a.m.	Mid-morning break
10:45 a.m.	Report on Canadian ST activities — David Kendall, NRC
11:15 a.m.	Report on space shuttle capabilities for science in the '90s
12:15 p.m.	Lunch
1:15 p.m.	Plenary discussion of Workshop goals and activities
2:00 p.m.	Telescience and Remote Science Operations in the 1990s - Dr. Joe Bredecamp, NASA Headquarters**
3:00 p.m.	Discipline group discussion sessions

Wednesday, September 14

8:30 a.m.	Discipline group meetings
10:15 a.m.	Mid-morning break
10:30 a.m.	General discussion of issues and development of the organization of final report
12:00 p.m.	Lunch
1:30 p.m.	Discipline meetings and writing activities

Thursday, September 15

8:30 a.m.	Discipline group writing and discussion periods
12:00 p.m.	Lunch
1:15 p.m.	Presentations of Discipline group recommendations
3:00 p.m.	Mid-afternoon break
3:30 p.m.	Final report review and discussion meeting
6:00 p.m.	Workshop dinner, Stanford Court Hotel, Menlo Park, informal comments: Dr. Stanley Shawhan

Friday, September 16

8:30 a.m.	Formal wrap-up presentations by discipline groups
10:15 a.m.	Mid-morning break
10:30 a.m.	Continuation of wrap-up presentations
12:00 p.m.	Lunch
1:15 p.m.	Left-over writing and departure activities

Alterations to Agenda

*ESA ST Activities—Andre Balogh, Imperial College, London
ESA Participation on Space Station—George Haskell, ESA
**Information Systems Strategic Planning Project—Michael J. Sander, Jet Propulsion Laboratory

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15. Supplementary Notes

Peter Banks: Stanford University, Stanford, California.
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Jack Kropp: TRW, Inc., Redondo Beach, California.

16. Abstract

This report summarizes the conclusions and recommendations reached at a Solar Terrestrial Science Strategy Workshop held at Stanford University on September 12-16, 1988. The panelists were U. S. scientists currently active in solar terrestrial research representing the science disciplines of upper atmospheric physics, ionospheric physics, space plasma physics, magnetospheric physics and solar physics. The charter given to this diverse group was: (1) To establish the level of scientific understanding to be accomplished with the completion of the current and near term worldwide programs; (2) Identify the significant scientific questions to be answered by future solar terrestrial programs, and the programs required to answer these questions; and (3) map out a program strategy, taking into consideration currently preceived space capabilities and constraints, to accomplish the identified program.

The report itself tends to summarize the objectives of the individual discipline groups, but also emphasizes the major themes which come from the entire group.

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