Adv. Space Res. Vol.4, No.7, pp.365-373, 1984
Printed in Great Britain.

0273-1177/84 $0.00 + .50

SOLAR-TERRESTRIAL RESEARCH OPPORTUNITIES — A LOOK TO THE FUTURE

Devrie S. Intriligator

Carmel Research Center, P.O.B. 1732, Santa Monica, CA 90406, U.S.A.

ABSTRACT

In the late 1980's and in the 1990's we will have the opportunity to increase our knowledge of the sun, the heliosphere, and their influences on the earth's magnetosphere/ionosphere/atmosphere system. We should be able to gain increased knowledge of the physical mechanisms that drive the sun, the three-dimensional structure of the heliosphere, and the flow of energy and momentum from the sun through the interplanetary medium to the magentosphere/ionosphere/atmosphere system. We also may be able to evaluate the influence of the solar radiative output on the earth's atmosphere. Through well-coordinated national and international efforts we can plan and carry forward successful programs to accomplish these scientific goals. Space missions, ground-based observing networks, and rocket and balloon campaigns are needed and should be well-coordinated. Wide and easy access of data will help ensure the effectiveness of these programs. Retrospective studies, theory, modelling, simulations, and data analysis are also vital elements of research in this area. There are important scientific opportunities for scientists from all countries.

INTRODUCTION

We are currently at a turning point in solar-terrestrial research. We have passed the era of mainly exploration and we have entered an era where we anticipate achieving an understanding of many of the fundamental underlying physical mechanisms responsible for the interconnections within the solar-terrestrial system.

Solar-terrestrial research is the study of the essential processes by which energy in all forms is generated by the Sun, is transported to Earth, and ultimately vitally influences the terrestrial environment. It deals with the direct irradiation of the upper atmosphere by the full spectrum of electromagnetic radiation and with the transport of particles and fields from the Sun, through the interplanetary medium, to and through the magnetosphere of the Earth and into its atmosphere. The principal science issue today in solar-terrestrial research is to understand this coupled system. Solar-terrestrial research is concerned with the critical complex interplay of physical and chemical processes in every element of the Sun-Earth system.

Today there are many significant opportunities in solar-terrestrial research. Based on our increased understanding in many subareas of solar-terrestrial research we recognize that many important fundamental questions concern the "interconnections" or the "coupling" of the solar-terrestrial system. The solar output reaches the earth either through electromagnetic radiation or the magnetized plasma streams of the solar wind. The electromagnetic radiation directly drives the circulation of the atmosphere, while the solar wind drives a diverse collection of fundamental phenomena ranging from the acceleration of particles in interplanetary space to geomagnetic storms and the aurora. A further complication results because the Sun is a variable star, with transient outbursts such as solar flares and long-term cyclic changes in solar magnetism.

The following open questions illustrate the major complex scientific dilemmas surrounding our understanding of the interconnections of the solar-terrestrial system:

1. What are the major mechanisms responsible for the generation of the solar magnetic field and for its interactions with the magnetospheric field? What are the effects of the ionosphere and atmosphere on the resulting interaction? We know that processes within the solar convection zone give rise to the magnetic field, which is carried toward the Earth by the solar wind plasma. The solar wind is deflected by the Earth's intrinsic magnetic field, thus producing the magnetosphere. The variable orientation of the interplanetary magnetic field with respect to the fixed orientation of the Earth's internal dipole field determines

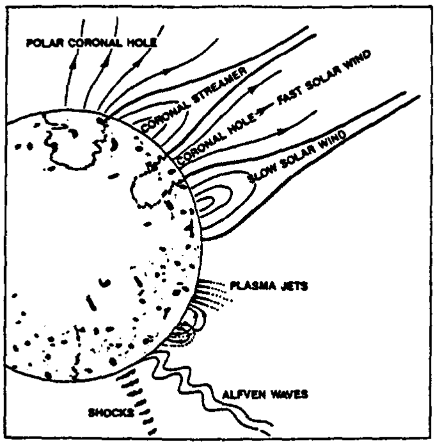


Fig. 1. The sun is a source of electromagnetic radiation, the solar wind plasma, and particles. Extending from visible features on the solar surface are a variety of magnetic structures.

the extent to which processes within the magnetosphere and the auroral zone perturb the ionosphere and atmosphere.

2. How do small changes in the solar radiative output influence the ozone chemistry of the atmosphere? What is the Sun's short-term and long-term variability in the relevant (175-242 nm) wavelength range and what are the corresponding variations in atmospheric ozone? We know that despite its thinness (0.3 cm at atmospheric pressure) the ozone layer plays an essential role in the preservation of life on Earth since it absorbs nearly all the potentially lethal solar-ultraviolet radiation that enters the atmosphere.

3. What is the response of the coupled Sun-solar wind-magnetosphere-ionosphere-atmosphere system to transient events originating on the Sun? What is the nature of the flare process? How does the resulting shock disturb the solar wind? What is its role in the local acceleration of particles and the perturbations of the interplanetary magnetic field? What are the important changes induced in the magnetosphere by the passage of the shock? What are the major chemical consequences of sudden enhancements in the level of atmospheric ionization from both radiative and particle energy? We know that transient events on the Sun give rise to both radiative and plasma effects. Solar extreme ultraviolet and x-ray outputs can be dramatically increased for short periods, producing substantial atmospheric chemistry

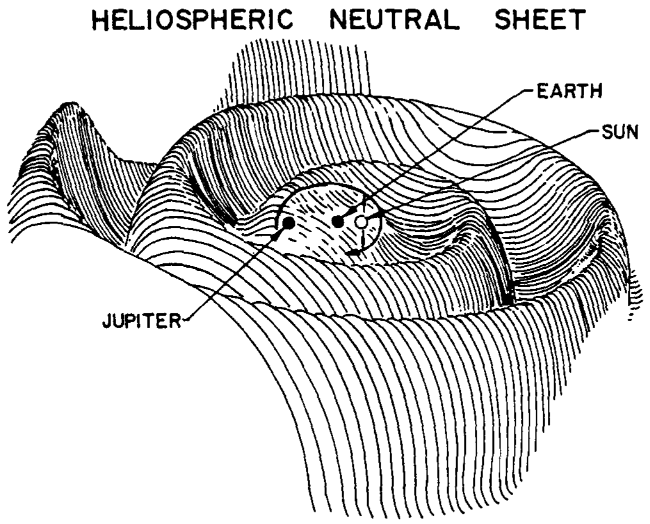


Fig. 2. The heliospheric neutral sheet. The solar wind carries some of the solar magnetic field through interplanetary space. We now know that the heliospheric neutral sheet or current sheet is similar to a "ballerina skirt". The sun is the center of an extensive and warped disk-like sheet in which electric currents flow azimuthally, that is around the sun. The average plane of the disk is approximately the plane of the equator of the sun's average dipole magnetic field, which may be tilted with respect to its equator of rotation. The sheet separates solar-interplanetary magnetic field regimes of nearly opposite or at least greatly different average direction.

perturbations related to both the ozone budget response and the enhanced ionization. A travelling shock wave in the solar wind triggers a violent magnetosphere response, resulting in strongly intensified auroral activity.

The solar-terrestrial system also provides us with a unique laboratory for investigating questions of astrophysics and of many other branches of science. The recent physics survey of the U.S. National Academy of Sciences recognizes that the increasing precision of measurements, numerical modeling, and theory applied to space-plasma problems amounts to a revolution in technique relative to 10 years ago. As a result, the study of space plasmas has become one of the primary motivations and experimental areas for basic plasma research. The solar-terrestrial system is the primary laboratory in which astrophysical processes of great generality can be studied in-situ. In addition, the sun is the only star available for close-up, detailed studies. The physical processes responsible for its structure and dynamic energy transformation phenomena are still not understood, but they are particularly important to the understanding of other main-sequence stars, and they serve as a model of many stellar phenomena. For example, study of solar activity is providing insight into stellar wind flows from the Beta Cephei class of pulsating stars such as Sigma Scorpius.

The magnetospheres of Earth and Jupiter are much more accessible than the magnetospheres of neutron stars or galaxies, and our knowledge of planetary magnetospheres has yielded important insights into how pulsars and radio galaxies may behave. Our studies provide knowledge of the evolutionary history of the Sun-Earth system and of the solar system. In the U.S. some of the plasma processes which are relevant to controlled thermonuclear power were first identified and analyzed within the context of solar-terrestrial research. High energy particle acceleration by shock waves - at the Sun and in the interplanetary plasma - is relevant to both astrophysics and laboratory plasma physics.

In the U.S. many scientists, people in funding agencies and in other positions in the government (including in the executive and legislative branches), and society in general realize the importance of continued scientific progress in solar-terrestrial research. The Committee on Solar-Terrestrial Research (CSTR) of the U.S. National Academy of Sciences is responsible for the "health" of solar-terrestrial research in the U.S. Two reports have been published in this area. Solar-Terrestrial Research for the 1980's /1/ emphasizes the need to develop a unified physical description of this coupled system. Other independent reports, such as Solar-System Space Physics in the 1980's: A Research Strategy /2/, and Space Plasma Physics: The Study of Solar-System Plasmas /3/ illustrate the unanimity of this conclusion among solar-terrestrial researchers and researchers in many related scientific fields. Recently the Committee on Solar-Terrestrial Research has issued the report National Solar-Terrestrial Research Program /4/ for the unified study of the important causal chain by which events on the Sun significantly influence our environment on Earth.

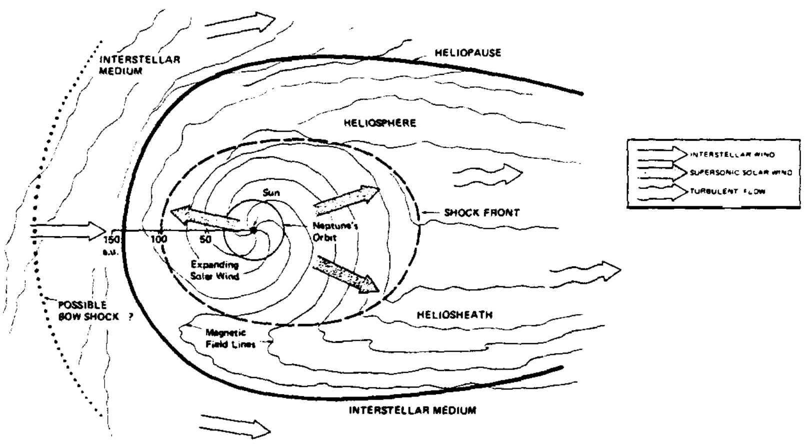


Fig. 3. One possible model of the heliosphere. The plane of the figure is the plane of the sun's equator, which is approximately the general plane of the planetary orbits. Pioneer 10 is making measurements beyond Neptune's orbit.

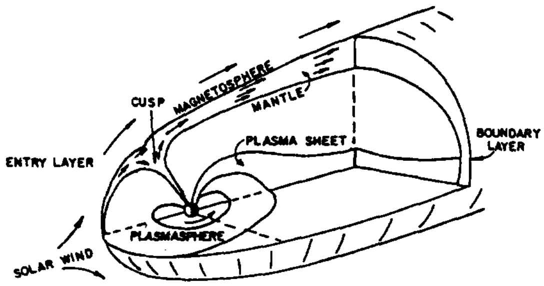
SELECTED RECENT ACCOMPLISHMENTS

The various elements of the solar-terrestrial system have been explored aggressively, and many of these elements are well understood individually. In some cases, major progress has been made in understanding the mutual interactions of these elements and their relation to other space plasma phenomena. Recent accomplishments in solar-terrestrial and space plasma research include:

- Mapping of the magnetospheres of the Earth and the major planets.
- Detailed observation of the solar wind and its transport properties and its interactions with planetary magnetospheres.

- Detailed observations of collisionless shocks and development of a substantial theoretical understanding.
- Observation and theoretical understanding of acceleration of particles to cosmic ray energies by collisionless shocks.
- Understanding that magnetohydrodynamic activity is central to the observed surface activity of the sun and stars.
- The observation that nearly all stars have coronal and stellar winds.
- Observations that radio emission accompanies energetic particles in magnetospheres and the beginning of a theoretical understanding of such emission (for example, of Type III radio bursts).

THE SIZE OF THE MAGNETOSPHERE



OUT TO THE MOON, A ROUGH ESTIMATE GIVES
V(MAGNETOSPHERE) ≈ 2×10^{16} (km)^3

COMPARISONS:

V(SOLID EARTH)	= 1.1×10^{12} (km)^3
V(ATMOSPHERE)	≈ 3×10^{10} (km)^3 OUT TO MESOSPHERE
V(OCEANS)	≈ 6×10^{8} (km)^3

Fig. 4. The size of the Earth's magnetosphere. We now have the technical knowledge to systematically study the earth's magnetosphere. The magnetospheric volume shown above is a lower bound since the recent ISEE-3 excursion through the geotail indicates that many important magnetospheric processes occur beyond 100 R_E. The ISTP spacecraft will study the magnetosphere.

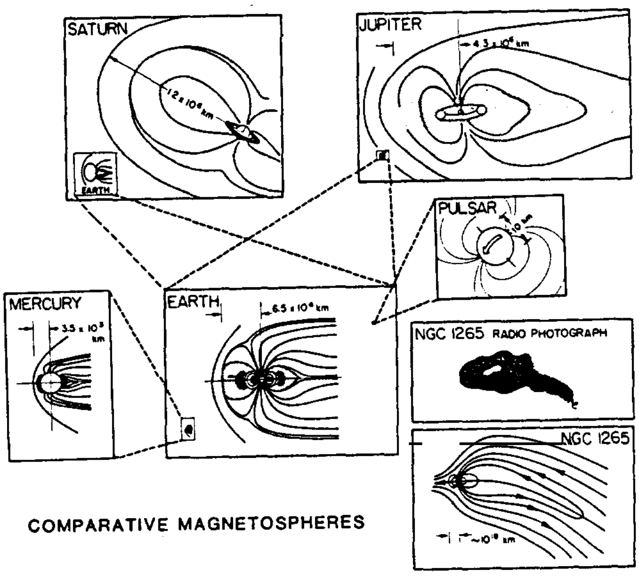


Fig. 5. Comparative magnetospheres. The solar-terrestrial system provides in-situ opportunities for studying astrophysical objects (e.g. the sun, the solar wind, magnetosphere.)

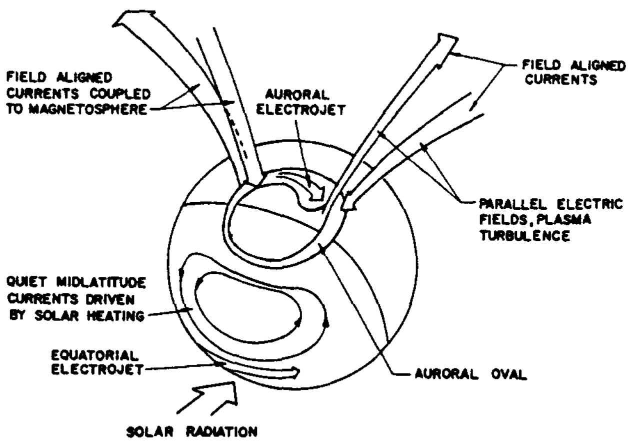


Fig. 6. Magnetospheric currents. Recently we have learned a great deal about the various current systems in the magnetosphere.

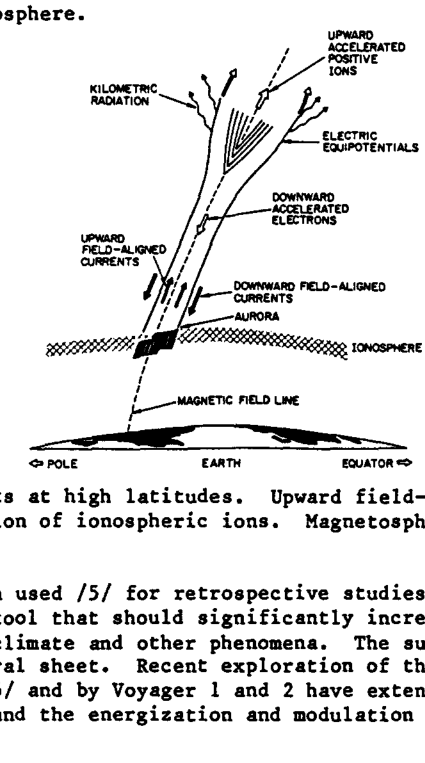


Fig. 7. Field-aligned currents at high latitudes. Upward field-aligned currents are associated with the acceleration of ionospheric ions. Magnetospheric particles are deposited in this region.

Recently beryllium 10 has been used /5/ for retrospective studies extending back to 1180 A.D. This is a powerful new tool that should significantly increase our knowledge of solar activity and its relation to climate and other phenomena. The sun's magnetic field gives rise to the heliospheric neutral sheet. Recent exploration of the outer regions of the solar system by Pioneer 10 and 11 /6/ and by Voyager 1 and 2 have extended our knowledge of the heliosphere, the solar wind, and the energization and modulation of higher energy particles.

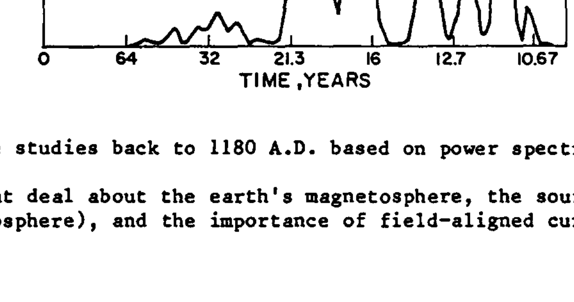


Fig. 8. Retrospective studies back to 1180 A.D. based on power spectra of beryllium 10 /5/.

We have learned a great deal about the earth's magnetosphere, the sources of its particles (e.g. solar wind, ionosphere), and the importance of field-aligned currents. We have also learned more about the relationship of the earth's magnetosphere to other planetary magnetospheres and to astrophysical objects.

There is evidence of the relationship of geomagnetic activity to thermospheric winds and of the relationship of solar activity to the heating of the earth's upper atmosphere. There is growing appreciation of the complexity of the stratosphere and of human influences (e.g. ozone layer, nuclear winter) on the near-earth environment.

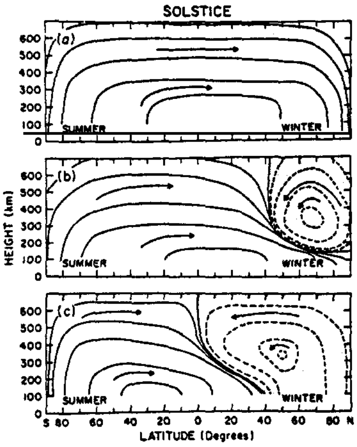


Fig. 9. Auroral and geomagnetic activity can affect thermospheric winds. Diagrams of the mean meridional circulation in the thermosphere at the time of the winter solstice in the northern hemisphere, for three levels of auroral or geomagnetic activity.

A LOOK TO THE FUTURE

Recent technological advances and theoretical understanding of the individual aspects are such that well-planned, adequately funded interdisciplinary efforts should lead to significant advances in our understanding of the solar-terrestrial system as a whole.

We recognize the need for a program that balances major observational efforts with a vigorous program of theory, data analysis, and ground-based and sub-orbital research. We also recognize that scientific effectiveness can be maximized by well coordinated national and international efforts. In solar-terrestrial research we have been fortunate to have had many highly successful international scientific efforts. We all know that these do not come about by chance, but rather through the hard work and dedication of scientists from many countries. The IGY, the IMS, the SMY, and STIP are each examples of these efforts. Looking to the future we see that international cooperation on spacecraft and possibly other observing networks can increase the scientific effectiveness of these efforts. The International Geosphere-Biosphere Program (IGBP) /7/ that is under consideration by ICSU could have a strong solar-terrestrial component that would enhance the scientific effectiveness of the IGBP and benefit solar-terrestrial research.

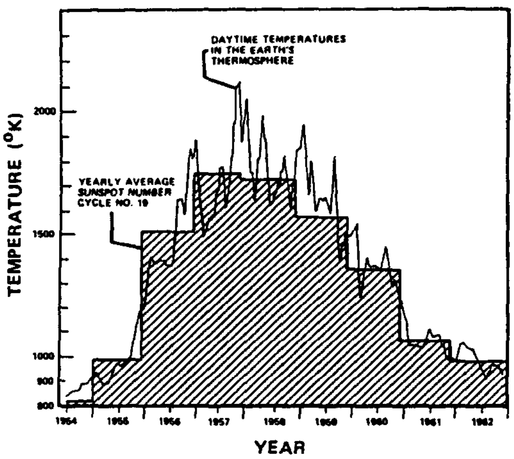


Fig. 10. Heating of the earth's upper atmosphere by solar activity.

As we look to the future we recognize the importance of major observational missions that are already well along in national and international planning: ISTP (International Solar-

Terrestrial Physics) Program; UARS (Upper Atmosphere Research Satellite); SOT (Solar Optical Telescope); ISPM (International Solar Polar Mission); and others.

ISTP is a joint program with the European-Japanese-U.S. program which plans for six new spacecraft systems in key regions to investigate the chain of processes from the solar interior to the Earth's magnetosphere and ionosphere. It is proposed to launch the ISTP spacecraft in the period from 1989 to 1992 and that the resulting data base be accessible to the worldwide scientific community. Measurements of the solar wind, the interplanetary magnetic field, and related parameters are essential to many phases of solar-terrestrial research. The first ISTP spacecraft, WIND (scheduled for launch in late 1989), will conduct these fundamental interplanetary observations. The SOLAR spacecraft will study the Sun's output; the Multipoint series will investigate the microphysics of the magnetopause; and POLAR, EQUATOR, and TAIL spacecraft will survey the flow of energy and particles through the magnetosphere.

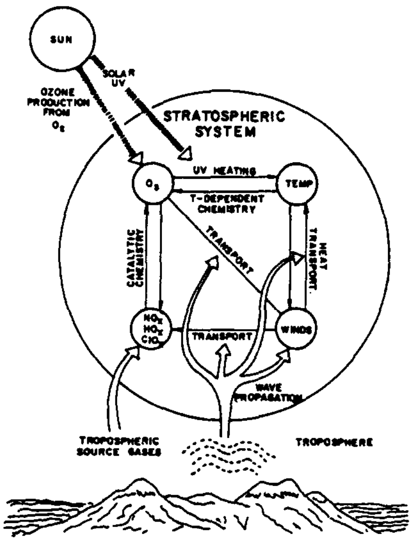


Fig. 11. The stratospheric system. The stratospheric system is a complex interplay among radiative, chemical, and dynamical processes. These are driven by solar radiation together with gases and energy from the troposphere. UARS will study this region.

UARS - the Upper Atmosphere Research Satellite - will provide for the first time the global data set required to the chemistry and dynamics of the upper atmosphere and the radiative and magnetospheric inputs of the upper atmosphere. The most effective means for acquiring comprehensive data on the upper atmosphere is the use of remote-sensing instruments on a satellite. Current technology has made it possible to develop instruments that can measure, with high precision on a global scale, incident solar radiation, ozone and other chemical species, and the temperature and motion of the upper atmosphere. The UARS program takes advantage of these capabilities.

The Solar Optical Telescope (SOT) will provide frontier observations of solar magnetic, velocity, and intensity fields with unprecedented spatial resolution. The SOT observations will be fundamental for understanding the physical bases of both solar variability (time scales from days to years) and solar activity (seconds to hours). After the initial flight and two or three reflights, each lasting 7 to 10 days, SOT is expected to become one of the major facilities of an Advanced Solar Observatory, which would function for at least 6 to 12 months as a free flyer or on a space platform.

Wide and easy access of data to the national and international scientific community would enhance the scientific effectiveness of these programs.

We also recognize that it is vital that there be new initiatives in data analysis to make full use of existing and planned ground-based and space-based data in order to investigate the many connections that exist between various components of the solar-terrestrial system. These initiatives in data analysis should have three elements: a) modeling, simulation, and analysis of existing data; b) computer networking; and c) workshops. Modeling, simulation, and analysis of existing data is needed to mine the rich lode of solar-terrestrial data. Preference should be given to research projects that investigate the interconnection of the various elements of the solar-terrestrial chain. The establishment of computer networks to enable a wide body of scientists to interchange data and models more effectively would enhance the scientific effectiveness of observational efforts. A series of workshops is

TABLE I U.S. NATIONAL SOLAR-TERRESTRIAL PROGRAM

MAJOR FLIGHT MISSIONS

ISTP - International Solar-Terrestrial Physics Program
UARS - Upper Atmosphere Research Satellite
SOT - Solar Optical Telescope

OTHER ESSENTIAL COMPONENTS

Initiative In Data Analysis
* Modeling, simulation, and analysis of existing data
* Computer networking - establish a "STR network"
* Workshops

Solar Variability
Systematic space and ground-based study of:
* "Solar constant"
* Solar UV spectral irradiance

Magnetosphere-Ionosphere Coupling
* Upgrade existing ground-based instruments (e.g. incoherent scatter radar, magnetometers, photometers)
* Develop new sensors for space and ground-based measurements

Increased Acquisition Of IMP-8 Data
* Solar wind - density, speed, temperature
* Interplanetary magnetic field

Coordinated Campaigns
* Triggered by events
* Predesignated "world days"

Ground-Based Synoptic Measurements
* Long-term program is essential
* Should include:
Solar optical (e.g. spectroheliograms); radio (e.g. dynamic radio spectra, radioheliograms); IPS (interplanetary scintillation); terrestrial magnetic activity (e.g. AE index); high energy cosmic rays (e.g. neutron monitors)

Middle Atmosphere Studies
* Support initiatives recommended by US MAP Panel /8/.
  - Theoretical and ground-based program: upper mesosphere radiation, chemistry, and dynamics; middle atmosphere waves and turbulence
  - Long-term measurements of dynamically and chemically important quantities

Rapid Turnaround Projects
* Test new instruments and theoretical ideas
* Use balloons, rockets, shuttle

Solar Seismology
* Understand dynamics of interior
* Probe convection zone
* Instruments and theory

Global Electric Circuit
* Electrodynamic coupling among troposphere, ionosphere, and magnetosphere
* Theory and observation
* (IGBP)

Educational Programs
* Train qualified students

Thermospheric Measurements
* Study effects of solar EM and particles
* Ionosphere/neutral atmosphere interaction
* Develop new ground-based techniques

Stokes Polarimeter
* Measure small-scale B, V fields on sun
* Determine relation to solar variability/activity

vital to assimilate and analyze interdisciplinary data. Studies that focus on the significant interconnection of links in the solar-terrestrial chain should be emphasized. The Study of Traveling Interplanetary Phenomena (STIP) sponsored by SCOSTEP is a good example of such an interdisciplinary study.

Space-based and ground-based national and international networks are needed to obtain the important long-term measurements of solar-variability (i.e., the total solar irradiance (the "solar constant") and the solar ultraviolet spectral irradiance); synoptic measurements of the solar-terrestrial system (i.e., solar wind (e.g., plasma and fields), solar optical data (e.g., spectroheliograms), radio observations (e.g., dynamic radio spectro, radioheliograms), interplanetary radio scintillations, terrestrial magnetic activity (e.g., Auroral Electrojet Index), ionospheric and atmospheric parameters (e.g., density and electric fields), and high-energy cosmic rays (e.g., neutron monitors).

In the U.S. we have identified a number of additional components as essential for a balanced program. These are listed below along with the elements discussed above.

Solar-terrestrial research has now reached a critical point, where a major step forward is possible. During the last decade, major discoveries and theoretical advances related to the individual components have taken place; these are now the base for the next step, which is to understand how these individual components interact. Of all the planets the Earth and its biosphere presents the widest range of interacting physical and chemical processes. We now have the technical resources to study the entire system as a whole on a day-to-day basis and on a global scale. We must work together and take this opportunity to rise to the challenge.

ACKNOWLEDGEMENTS

This work was supported in part by contract NASW - 3914 with NASA Headquarters.

REFERENCES

1. Solar-Terrestrial Research for the 1980's, H. Friedman and D.S. Intriligator, co-chairman, Committee on Solar-Terrestrial Research, National Research Council, U.S. National Academy of Sciences, Washington, D.C., 143 pp., 1981.

2. Solar-System Space Physics in the 1980's: A Research Strategy, C. Kennel, chairman, Committee on Solar and Space Physics, Space Science Board, National Research Council, U.S. National Academy of Sciences, Washington, D.C., 82 pp., 1980.

3. Space Plasma Physics: The Study of Solar-System Plasmas, S. Colgate, chairman, Space Science Board, National Research Council, National Academy of Sciences, Washington, D.C., 96 pp., 1978.

4. National Solar-Terrestrial Research Program, D.S. Intriligator, chairman, Committee on Solar-Terrestrial Research, National Research Council, U.S. National Academy of Sciences, Washington, D.C., 39 pp., 1984.

5. Cini Castagnoli, G., G. Bonino, M.R. Attolini, M. Galli, and J. Beer, I cicli solari nell'ultimo millennio nel ^{10}Be e ^{18}O nei ghiacci polari e nella termoluminescensza di un sedimento del mar tirreno, Nuovo Cimento, in press, 1984.

6. Intriligator, D.S., and W.D. Miller, Plasma shocks and energetic particles in the outer solar system: trapping and asymmetry - observations from Pioneers 10 and 11, J. Geophys. Res., 87, 4354, 1982.

7. Toward an International Geosphere-Biosphere Program, H. Friedman, chairman, National Research Council, U.S. National Research Council, U.S. National Academy of Sciences, Washington, D.C., 77 pp., 1983.

8. Research Recommendations for Increased U.S. Participation in the Middle Atmosphere (MAP), J. Mahlman, Chairman, Panel on MAP, Committee on Solar-Terrestrial Research, National Research Council, National Academy of Sciences, Washington, D.C., 12 pp., 1984.