THE OPEN PROGRAM: AN EXAMPLE OF THE SCIENTIFIC RATIONALE FOR FUTURE SOLAR-TERRESTRIAL RESEARCH PROGRAMS

D. J. Williams
NOAA Space Environment Laboratory
Boulder, Colorado 80303

ABSTRACT

The field of solar-terrestrial physics has evolved to a point where quantitative theoretical modeling and cause-effect predictive techniques can be foreseen. Instrumentation now exists to quantitatively test these theories and lead to a significant improvement in our understanding of the solar-terrestrial environment. The proposed Origins of Plasma in the Earth's Neighborhood (OPEN) program will be used to trace this theoretical and experimental evolution and describe a solar-terrestrial research scenario for the 1980's which includes specific problems related to solar and interplanetary dynamics.

1. INTRODUCTION

Exploration of the Earth's nearby space environment has revealed a dynamic and complex system of interacting plasmas, magnetic fields, and electrical currents surrounding our planet. This region, comprising the magnetized solar wind plasma plus the resulting perturbation in the heliosphere caused by the presence of the magnetic Earth, we call "geospace" (see Figure 1). Here plasma physics determines the behavior of matter on spatial and temporal scales vastly different from those that can be duplicated in earth-based laboratory devices. Geospace thus affords a unique and readily accessible laboratory for in-situ investigation of cosmic plasma processes. Through these plasma processes energy from matter expelled by the Sun is fed into the Earth's environment, constituting a small but highly significant part of our total solar energy budget.

The scientific thrust of the OPEN[1] program is:

1) to trace the flow of matter and energy through the system from input by the solar wind to ultimate deposition into the atmosphere;

2) to understand how the individual parts of the closely coupled, highly time-dependent geospace system work together;

M. Dryer and E. Tandberg-Hanssen (eds.), Solar and Interplanetary Dynamics, 507-522.

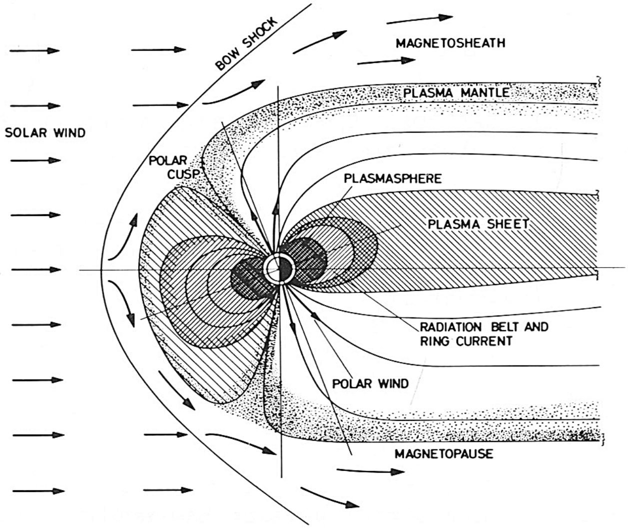


Figure 1. The major plasma regimes of geospace.

3) to understand the physical processes controlling the origins, entry, transport, storage, acceleration and loss of plasma in the Earth's neighborhood; and,

4) to assess the importance to the terrestrial environment of variations in atmospheric energy deposition caused by geospace plasma processes.

Previously, the near-Earth space environment has been explored and studied primarily as a system of independent component parts--the interplanetary region, the magnetosphere, the ionosphere and the upper atmosphere. From these earlier explorations, we now know that this environment--geospace--is a complex system composed of highly interactive parts whose total behavior differs significantly from a simple linear sum of the individual components. While previous programs have advanced our understanding of these geospace components individually, an understanding of geospace as a whole requires a planned program of simultaneous observations and theoretical studies keyed to a global assessment of the production, transfer, storage and dissipation of energy throughout this system. It is our current understanding of the various geospace components plus the long-awaited availability of required instrumentation that allow us, for the first time, to define and plan a comprehensive study of geospace as a whole.

The past twenty-one years have brought us from the era of discovery, through an era of exploration, to the beginning of an era of understanding of the complex physical processes in the geospace system. Table 1 shows examples of this process.

Table 1.

EVOLUTION OF IN-SITU GEOSPACE RESEARCH

DISCOVERY	VAN ALLEN RADIATION BELTS	
	SOLAR WIND	
	MAGNETOSPHERE	
EXPLORATION	BOW SHOCK	CUSP
	MAGNETOSHEATH	MANTLE
	MAGNETOPAUSE	AURORA
	TAIL	PLASMASPHERE
	NEUTRAL SHEET	RING CURRENT
	PLASMA SHEET	SUBSTORMS
BEGINNINGS OF AN UNDERSTANDING	PARTICLE PRECIPITATION	– EM CYCLOTRON INSTABILITIES
	AURORAL PRECIPITATION	– ES CYCLOTRON INSTABILITIES PARALLEL E FIELDS
	PARALLEL E FIELDS	– ANOMALOUS RESISTIVITY DOUBLE LAYERS
	SUBSTORMS	– TEARING MODE INSTABILITY MERGING

The discovery period was marked most notably by the discovery of the Van Allen radiation belts and the solar wind. The exploration period was characterized by the morphological delination of geospace components into localized substructures such as the bow shock, magnetosheath, plasmasphere, plasma sheet, neutral sheet, mantle, polar cusps, ring current, etc. The recent beginning of our understanding of specific geospace components and substructures has been characterized by the application of plasma physics to interpret observed phenomena such as particle precipitation via electromagnetic cyclotron instabilities, strong auroral precipitation via electrostatic instabilities, parallel electric fields via anomalous resistivity and double layers, substorms via the tearing-mode instability, and Alfvén waves in the solar wind.

It is clear that the scientific thrust of OPEN is intimately involved with a variety of questions in space plasma physics. In pursuing these questions OPEN will address directly the problems of magnetic field reconnection, the interaction of plasma turbulence and magnetic fields, the behavior of large-scale flows of plasma and their interaction with each other, acceleration of energetic particles, particle confinement and transport, and collisionless shocks.

2. THE OPEN OBSERVATIONAL LABORATORIES

Embedded in the geospace system are two major plasma sources--the solar wind and the terrestrial ionosphere--and two major storage regions --the geomagnetic tail and the near-Earth plasma sheet and ring current. These four basic geospace regions are interconnected by a complex network of transport processes which act to determine the highly interactive behavior of the system as a whole. This is illustrated by the topologically similar Figures 2 and 3. Consequently, it is necessary to

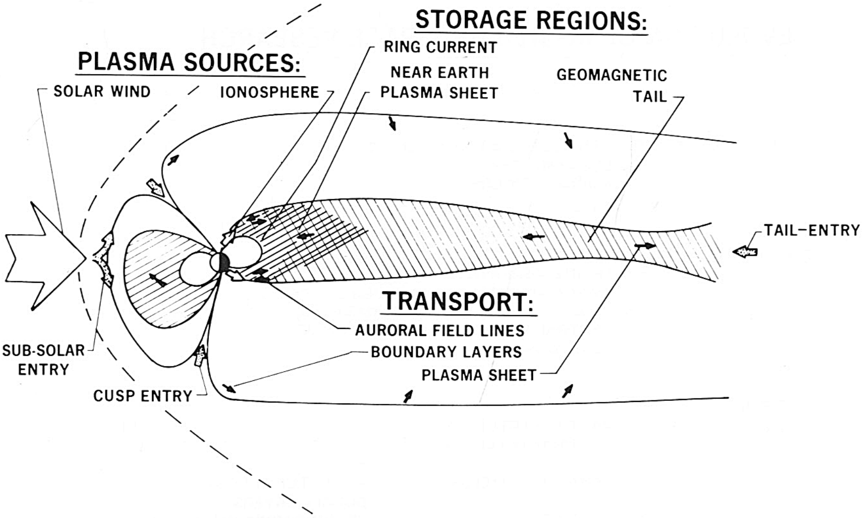


Figure 2. A schematic view of the entry of plasma from the solar wind and ionosphere source regions, of the ring current and tail plasma sheet storage regions, and of some of the transport paths which tie the system together. Energization and dissipation can occur in all regions.

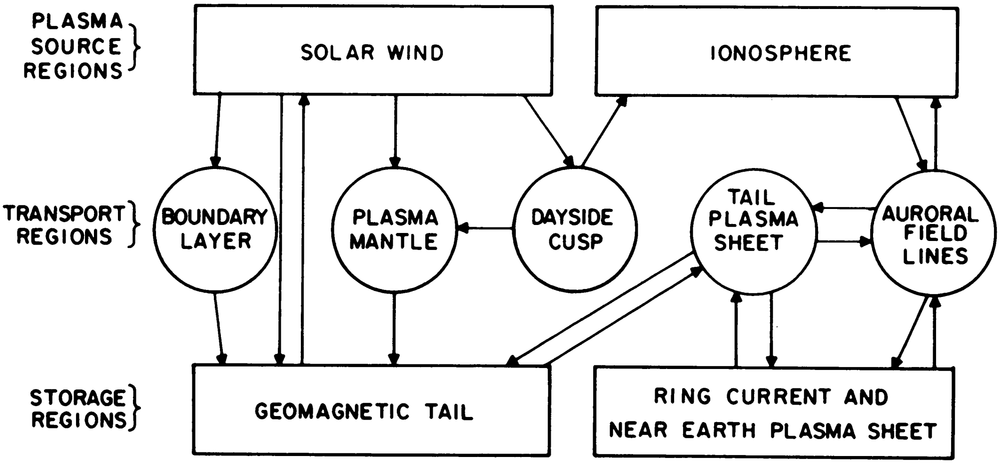


Figure 3. A simplified diagram of the major transport paths that couple geospace source and storage regions. Since processes are highly time-dependent, each of the key regions must be sampled simultaneously in order to understand the behavior of the system as a whole. The OPEN program will provide the first comprehensive attack on this problem.

obtain simultaneous, multipoint measurements in each of these key regions in order to meet the objective of a global view of the energy flow throug the geospace system.

The OPEN Program described here is the minimum program capable of a global geospace study. In this program an observing laboratory with orbit-adjust capability is stationed to observe each of the two source and two storage regions. These laboratories are:

1) Interplanetary Physics Laboratory (IPL)

The IPL will be stationed in the upstream solar wind near the sunward libration point. It will:

- determine the characteristics of the solar wind source plasma,
- provide the complete plasma, energetic particle and magnetic field input function for the complementary magnetospheric satellites, and
- determine the magnetospheric input to interplanetary space.

(2) Geomagnetic Tail Laboratory (GTL)

The GTL will utilize lunar swing-by orbit adjustments in order to maintain a distant apogee (80-250 R_E) in the magnetotail. The GTL will:

- determine for the first time the characteristics of the distant geomagnetic tail,
- with complementary magnetospheric satellites help determine the role of the distant tail in substorm phenomena and in the overall magnetospheric energy balance (energization, transport, storage and dissipation),
- separate out the ionospheric and solar wind contribution to geomagnetic tail plasma, and
- search for acceleration (reconnection, parallel electric fields, induction, etc.) processes.

(3) Polar Plasma Laboratory (EPL)

The PPL will be placed in a highly eccentric polar orbit. An orbit adjust capability will be available to vary apogee radius in the 4-15 R_E range. The PPL will:

- with complementary magnetospheric satellites help determine the role of the ionosphere in substorm phenomena and in the overall magnetospheric energy balance,
- measure energy input through the dayside cusp and mantle regions,
- determine characteristics of ionospheric plasma outflow from parallel electric field acceleration regions,

- study characteristics of the auroral acceleration regions, and
- provide global multispectral auroral images of the footprint of the magnetospheric energy deposition into the ionosphere and atmosphere.

(4) Equatorial Magnetosphere Laboratory (EML)

The EML will be located in an equatorial 2 x 12 R_E orbit. It will have an orbit-adjust capability to provide later a deep tail orbit, thereby allowing (with GTL) simultaneous 2-point samples of the distant tail. The EML will:

- with complementary magnetospheric satellites help determine the substorm trigger mechanism and the overall magnetospheric energy balance,
- provide direct observations of the interactions of geomagnetic tail and ionospheric plasmas in the equatorial magnetosphere,
- measure the transport and storage of ionospheric and tail plasma in the near-Earth plasma sheet and ring current, and
- measure the coupling of the solar wind to the magnetosphere at the subsolar magnetopause.

The orbit-adjust capability provides an observing flexibility required by the comprehensive goals of the program. Figures 4 and 5 illustrate this concept of the OPEN Program by showing two of many possible observational configurations which will be used to study the global energy transfer problem. The figures schematically show the major source and storage regions, locations of known and suspected acceleration and dissipation, and the major transport avenues which interconnect the basic geospace components.

Figure 4 shows the IPL measuring the input boundary conditions to the magnetospheric system. The GTL, in the distant tail, will study solar wind and ionospheric plasma entry and the effects of varying solar wind input on entry, storage, acceleration, dissipation and transport throughout these heretofore unexplored regions. Simultaneously the PPL and the EML will perform complementary observations covering the high latitude and subsolar magnetopause regions. In this case, not only will the overall problem of entry be addressed, but also the connections between the entry regions will be established by the simultaneous observations from the OPEN laboratories.

In Figure 5, the IPL and GTL perform functions similar to those described in Figure 4. However, the PPL has been placed in a low apogee orbit to measure directly ionospheric acceleration and output to the magnetosphere and to measure energy deposition into the atmosphere via multispectral auroral imaging. To complete the picture of overall energy flow, the EML will perform simultaneous observations of energy flow, storage, acceleration and dissipation in the nightside equatorial

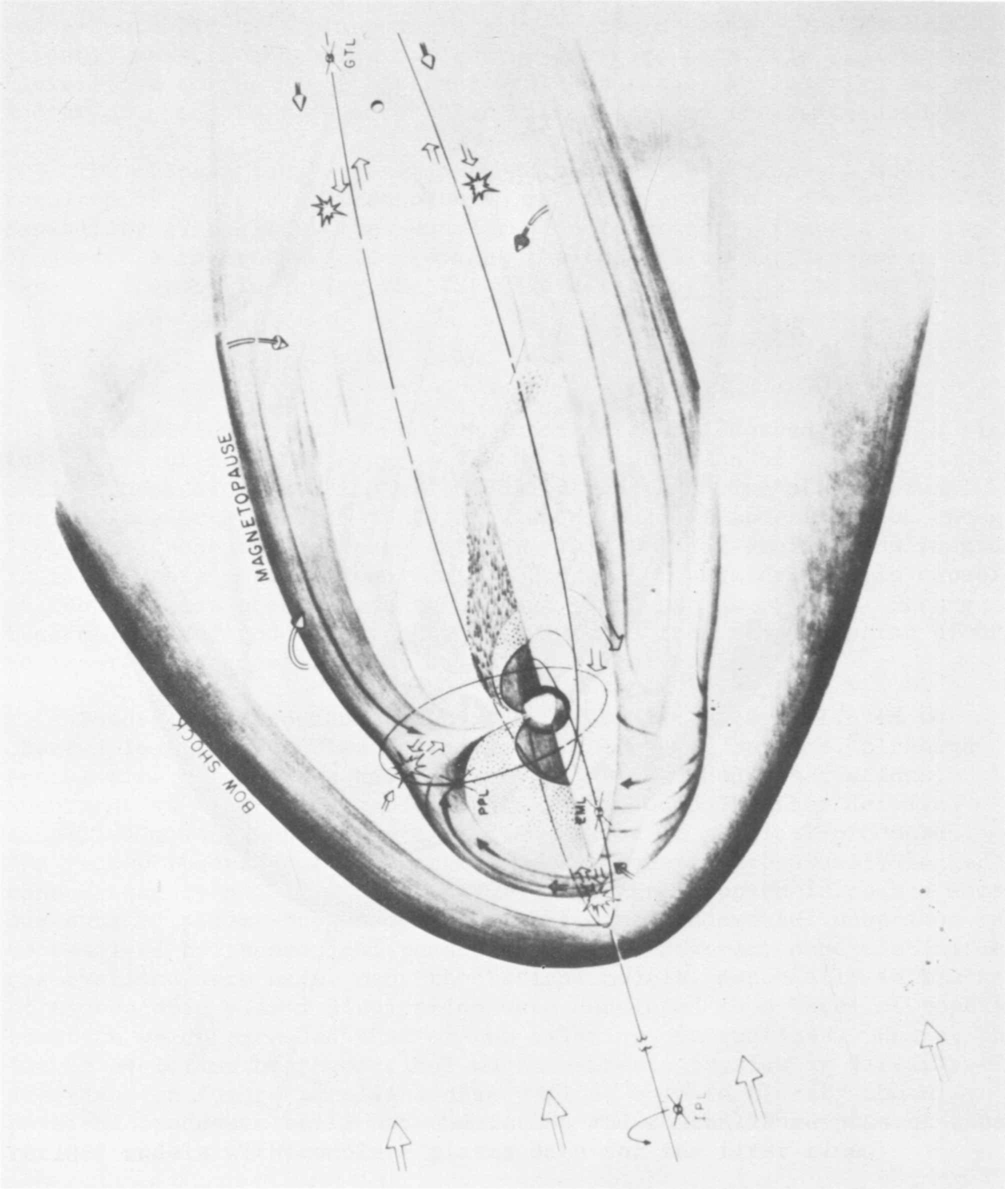


Figure 4. Example OPEN configuration for entry studies. Explosive symbols represent energization, three-dimensional arrows represent plasma entry into the magnetosphere, and open arrows represent transport. In this configuration the IPL measures the solar wind input; the PPL (in its high apogee orbit) and the EML measure entry, energization and transport spanning the dayside magnetopause from the subsolar point through the high latitude cusp regions; and the GTL measures entry, energization and transport in the distant, unexplored tail regions.

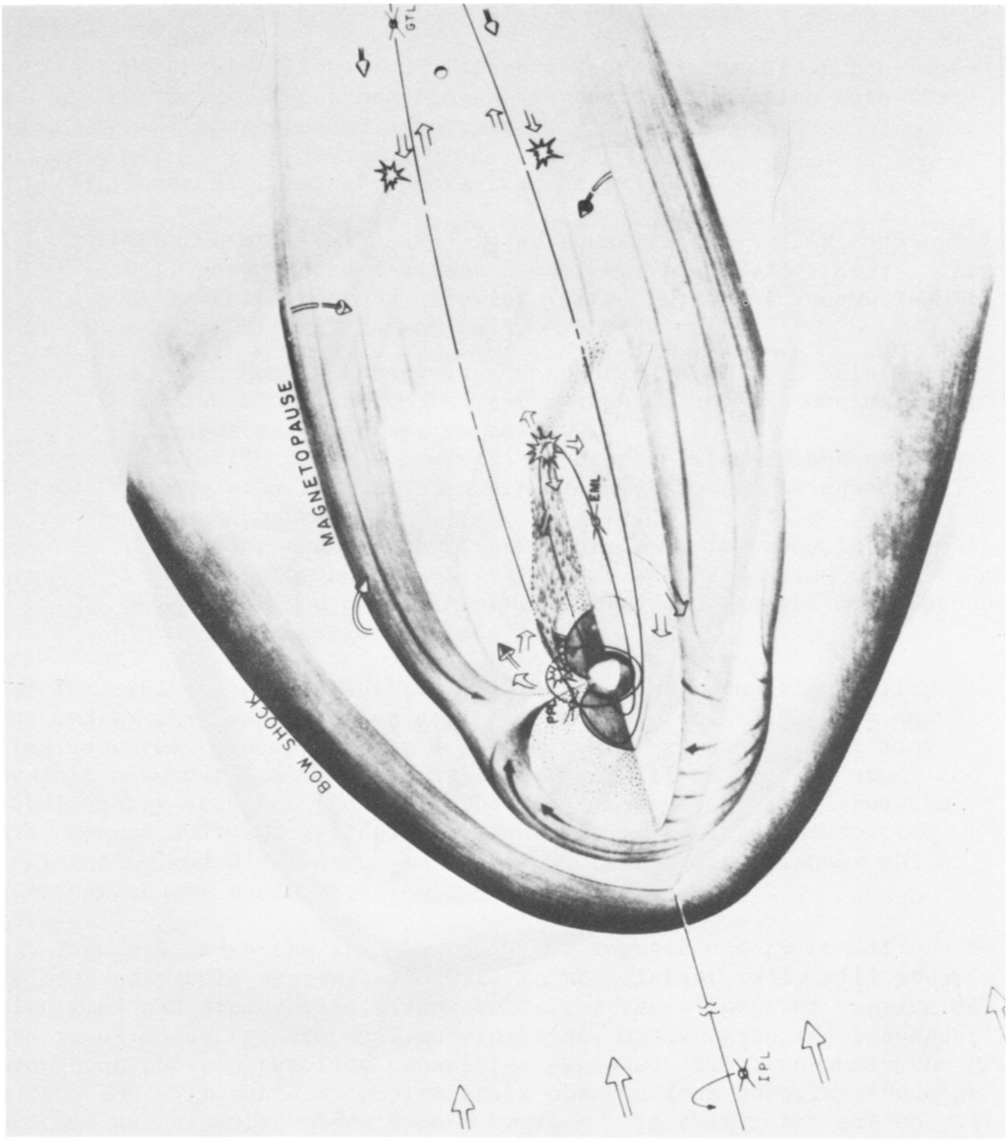


Figure 5. Example OPEN configuration for internal magnetospheric plasma flow studies. Symbols are the same as in Fig. 4. In this configuration the IPL again measures the solar wind input. However, the PPL, now in its low apogee orbit, measures the ionospheric output to the magnetosphere and via multispectral imaging measures the atmospheric energy deposition. The EML (now in the nightside hemisphere), and the GTL measure plasma mixing, energization, transport and storage in the respective near-earth plasma sheet, ring current and geomagnetic tail energy reservoirs.

magnetosphere--a region, largely unexplored, in which the ionospheric and geomagnetic tail plasmas are thought to interact. The EML will directly measure the amount of energy diverted from this region along field lines to the atmosphere and will determine the relative amount of energy diverted to flow across the field lines to the magnetopause.

The observational flexibility illustrated by Figures 4 and 5 is required by the overall geospace energy flow problem. The orbit-adjust capability also allows the transfer of a laboratory from one key region of geospace to another and provides the capability for two-point tail observations by injecting the EML into a tail orbit at the end of the primary mission.

3. THEORY

In addition to the observing laboratories discussed above, a vital ingredient of the OPEN Program is the incorporation of a strong and active theoretical studies and modeling program. The observational goal of the OPEN Program is to provide an overall assessment of energy flow throughout the geospace system. The physical goal of the program is to use this observational data to construct physical models capable of cause-effect predictions throughout the geospace system. Strong theoretical and modeling input is envisioned from the inception of OPEN to insure the accomplishment of this physical goal.

Theoretical progress in physics is usually closely linked to observational discoveries and advances. In space physics, although speculative predictions have occasionally preceeded observations, quantitative theoretical models have developed only after detailed satellite measurements have clarified the basic physical processes. The reason theories of the earth's magnetosphere have usually lagged observation is not hard to discern. The magnetosphere is such a complex and dynamic plasma-physical system that most fundamental questions cannot be resolved by theoretical reasoning alone. However, once the initial observations were made, many theoretical models, especially in the area of microscopic plasma dissipation were developed to a level of sophistication which exceeded that of the existing observations. Hence, the future evolution of theoretical magnetospheric physics is directly dependent on future satellite observations both to clarify those physical processes still not understood and to challenge present theoretical models with complete plasma data for the first time.

The OPEN Program will settle several basic questions which have seriously inhibited previous theoretical efforts. The first question is what is the total mass, momentum, and energy budget to the magnetosphere? This bound represents the most basic constraint on all quantitative magnetospheric models and processes. The structure of the distant tail, the closure of the plasma mantle flow within the tail, the determination of the relative importance of reconnection and viscous transport, the structure of the dayside equatorial and polar magnetospheric plasma, and the temporal morphology of magnetic storms and the ring current, substorms, and magnetospheric configuration changes are all theoretical issues which can be resolved only by the simultaneous observations from the four OPEN spacecraft. In these areas either the absence of information or major uncertainties in previously obtained data have stymied theoretical progress. Fairly detailed theoretical models have been developed to describe the microscopic plasma turbulent dissipation in the solar wind, the radiation belts, and in the auroral arc field-aligned current regions. For these problems, OPEN will obtain high resolution measurements of the complete ion, energy, and pitch-angle distributions which can then be directly compared with the theoretically expected distribution functions. Only when such microscopic comparisons are achieved can theory advance to quantitatively more accurate models.

As fundamental plasma dynamics are revealed and clarified by observations, theorists can begin to utilize the powerful computational tools of plasma particle simulation and hydromagnetic fluid codes in order to develop a complete understanding of solar wind and magnetospheric processes. Each microscopic dissipation mechanism should be studied until quantitative agreement with observations is achieved. Only then can these microscopic processes be incorporated into the development of global models of the entire geospace system. The ultimate goal of theory will be to construct global models that accurately predict the time-dependent response of this system. A first step toward this goal will be the global observational study of geospace by the OPEN mission.

4. A SAMPLE PROBLEM

It is not only the present scientific maturity of geospace research that enables us to define and conduct a positive attack on the goal of assessing mass, momentum and energy flow throughout the geospace system. Without the evolution of spacecraft to their present weight, power, telemetry rate and orbit-adjust capabilities the measurements required could not be made. Spacecraft evolution and recent instrumentation breakthroughs now allow the measurement of a complete set of key physical parameters of the geospace plasma to be obtained. Critical instrumentation which has been developed recently or is being developed for approved missions includes ion composition and charge state measurements covering the few eV to several MeV energy range, three-dimensional plasma and energetic particle distributions, auroral imaging and active particle loss-cone scan instrumentation.

Here we give one example of how present scientific understanding couples with new instrumentation developments and makes the OPEN Program possible. Of the many examples available from geospace research, perhaps one of the clearest is the long standing problem of the earth's ring current. The ring current is one of the two major energy storage reservoirs in geospace and is responsible for the occurrence of worldwide geomagnetic storms. The major questions associated with this geospace energy reservoir are: (1) what is its source? (2) what are its constituent charged particles? (3) how does it develop? (4) how does it

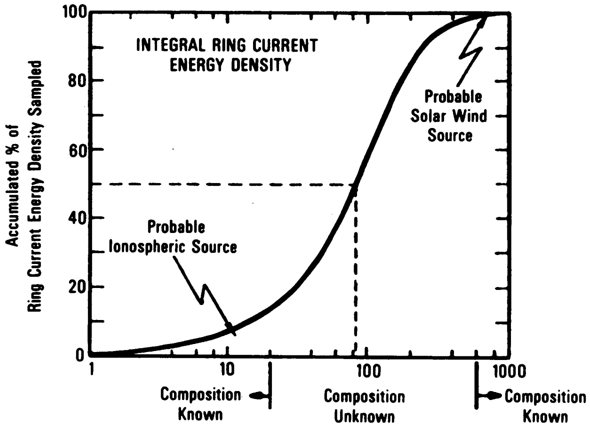


Figure 6(a). A major storage region--the earth's ring current. The accumulated percentage of ring current energy density is shown versus energy. Presently available direct composition measurements and inferred sources also are shown.

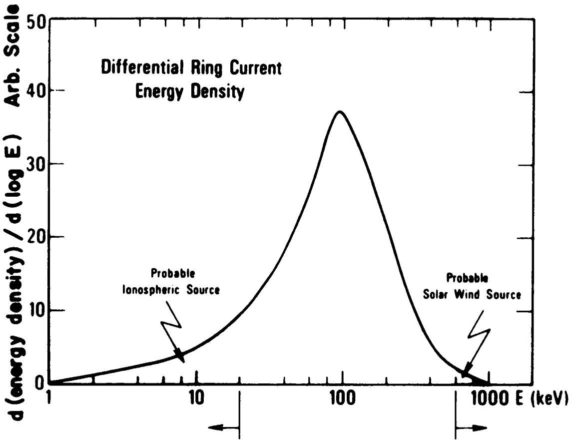


Figure 6(b). The differential d(Energy Density)/D(Log E) of curve (a) versus energy.

dissipate? and (5) how does it interact with the other components of geospace? Several years ago it was thought that the basic answers to these questions were known--the source of the ring current was assumed ultimately to be the solar wind, it was therefore made up of protons, it probably developed via convection of plasma from the geomagnetic tail, it dissipated via charge exchange with the neutral atmosphere, and it had no strong interaction with other geospace components.

The limited composition measurements that have become available in the past few years have completely changed our concept of this major geospace energy reservoir. Figure 6 summarizes what is known of the ring current at present. Direct composition measurements exist for only the low energy tail (< 20 keV) and high energy tail (> 600 keV) of the ring current distribution. No composition measurements exist for 80-90% of the energy density in this storage region. In addition, we also now know that the interaction of the ring current hot plasma with the cold plasma of the ionosphere results in the stimulation of plasma instabilities which cause significant ring current dissipation and ionospheric heating. The most probable source identified from the existing composition information also is indicated in Figure 6. Note that the low energy ions have a probable ionospheric source and the high energy tail has a probable solar wind source. No information exists as to how these sources mix to produce the bulk of the ring current distribution.

Thus we see that none of the problems previously posed concerning the ring current have yet been solved due to the present lack of required measurements. However, our present scientific understanding allows us to specify the problems quantitatively, and recent instrumentation advances now permit us to implement a program for their solution. Note that for this specific example simultaneous measurements are required of the ionospheric source, the solar wind source, the convecting geomagnetic tail plasma, and the equatorial mixing, acceleration, storage, transport and dissipation of these plasmas.

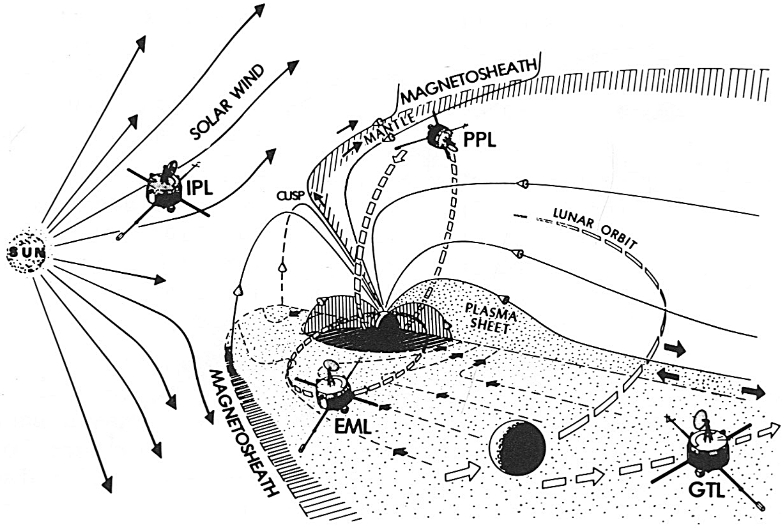
A similar situation exists if we are to understand many other important problems such as the role of the remarkable auroral magnetic field-aligned acceleration regions in coupling the magnetospheric energy storage regions to energy dissipation regions in the atmosphere, or the global dynamics of the geospace system during substorm energy release events, or the role of the distant geomagnetic tail in the solar-terrestrial plasma chain.

5. OPEN SUMMARY

To pursue the goals defined for OPEN a program of correlated ground-based observations is required. While the direct energy input represented by particle precipitation into the atmosphere will be measured by the PPL via multi-spectral auroral imaging, another intense and complementary atmospheric energy input exists via Joule heating due to large currents flowing at low altitudes. To assess this additional heating it is necessary to have ground-based observations of electric fields, conductivities, and currents. Thus an active program of radar, magnetometer, photometer and riometer observations must be conducted simultaneously with the OPEN spacecraft measurements. Figure 7 thus summarizes the main elements of the OPEN Program.

6. TIMELINESS AND RELATION TO SOLAR-TERRESTRIAL AND HELIOSPHERE STUDIES

1) It is the next logical scientific thrust in geospace research. Our understanding has evolved from an early exploratory phase through a stage of detailed, localized investigations to our present capability of undertaking a comprehensive, global program.



- Interplanetary Physics Laboratory (IPL), Sunward Libration Point
- Geomagnetic Tail Laboratory (GTL), Remain in Tail via Lunar Assist, 80-250 R_E Apogee
- Polar Plasma Laboratory (PPL), Highly Eccentric Polar Orbit, 4-15 R_E Apogee
- Equatorial Magnetosphere Laboratory (EML), Equatorial 2 x 12 R_E, Orbit
- Theoretical Studies and Modeling Program, Centralized Data Base
- Ground Based Observations

Figure 7. A summary of the elements of the OPEN program. Each OPEN spacecraft will have propulsion systems which provide substantial orbit change capability so that a number of different orbit configrations can be utilized during the course of the program.

2) New instrumentation developments have also become available. We can now, for the first time, scientifically and technically define the program, and normal scheduling will implement the program in the mid-1980's.

3) OPEN is a strong, self-contained program in its own right. However, it is also a key element in a larger, overall solar-terrestrial program for the 1980's. Together with the Solar Polar Mission and the Upper Atmosphere Research Satellite, OPEN will permit us to conduct a coherent study of the transport of mass, momentum and energy from the sun through the heliosphere, the magnetosphere, and the ionosphere and into the atmosphere.

4) Studies of the magnetosphere and heliosphere are complementary, and simultaneous, coordinated investigations will be synergistic. In both the heliosphere and magnetosphere there are bulk motions of magnetized plasma, irregular motions of energetic charged particles, and beams

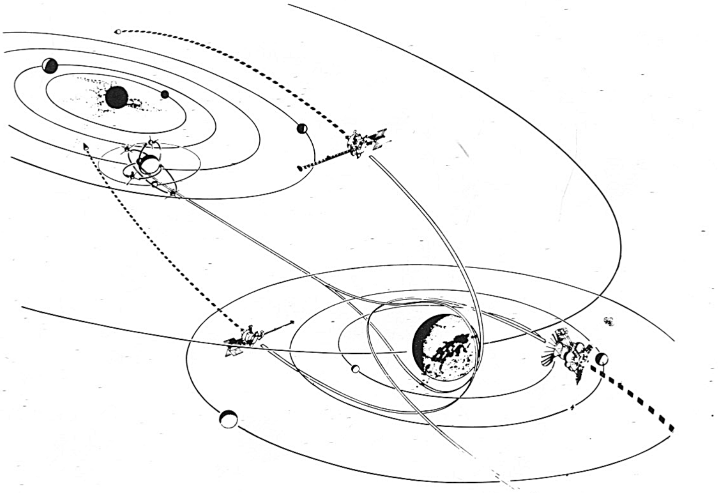


Figure 8. A possible solar terrestrial studies configuration in the 1980's. Shown are the OPEN laboratories, the Solar-Polar spacecraft, and the Galileo orbiter. Voyagers 1 and 2 will be in the ecliptic at distances of ∿ 8 AU and 15 AU.

of suprathermal ions and electrons. Similar types of plasma physics problems exist in both regions: what are the sources of plasmas, magnetic fields and energetic particles, how are thermal plasmas and energetic particles accelerated to form directed flows and suprathermal populations, and what are the energy transport and "loss" (conversion) processes? Previous studies have already shown that an understanding of physical processes in the magnetosphere can contribute to understanding processes in the heliosphere, and vice versa. The 1980's provide a timely opportunity for an organized effort to study problems common to both fields.

The OPEN study is part of an investigation of solar-terrestrial dynamics (Figure 8). It will take place during an investigation of global heliospheric dynamics by: (1) the International Solar Polar Mission (which will move from near Jupiter at 5 AU and pass over the sun's poles at a distance of 1 to 2 AU, (2) Voyager-1 and -2 (which will be in the ecliptic, moving between ∿ 8 AU and 15 AU), and (3) Galileo (in orbit around Jupiter). The IPL, stationed in the solar wind near earth, is a vital part of both the heliospheric and geospace studies. It will serve as a baseline for heliospheric investigations and a remote sensor of solar conditions. It will identify the processes between the Sun and Earth which link solar and terrestrial activity, and it will provide input functions for magnetospheric studies at Earth and, to some extent, at Jupiter.

5) Since geospace-like systems appear to be common elements throughout the universe (Figure 9) the knowledge gained from the OPEN

Program can be applied directly to various planetary and astrophysical studies. While the boundary conditions and scale sizes vary significantly from one system to another, we expect that a firm understanding of the overall geospace system will contribute fundamentally to studies of other cosmic plasma systems.[2,3]

6) A recent comprehensive study of space plasma physics[2] has shown that this field is of fundamental significance and that future progress in the field will depend on a balanced program of theoretical and observational studies that can systematically address basic scientific problems. OPEN is directly responsive to the specific recommendations of that study.

7) Knowledge gained of the geospace system has already been used to provide routine and specialized services to societal systems affected by geospace perturbations.[2,4,5] For example, alerts, warnings and forecasts of conditions throughout the geospace system are supplied to national defense systems and to communication, power and oil exploration industries as an aid to their day-to-day operations.[5] Variations in the geospace environment also lead to significant variations in energy deposition in the atmosphere and may have important consequences in the Earth's weather and climate. Thus an understanding of the geospace system as a whole is expected to have practical benefits. OPEN can develop the physical basis for assessing solar wind particle and field perturbations to atmospheric processes and for routinely monitoring those space plasma processes that affect satellite communications, satellite orbit lifetimes, and terrestrial power and exploration geophysics systems.

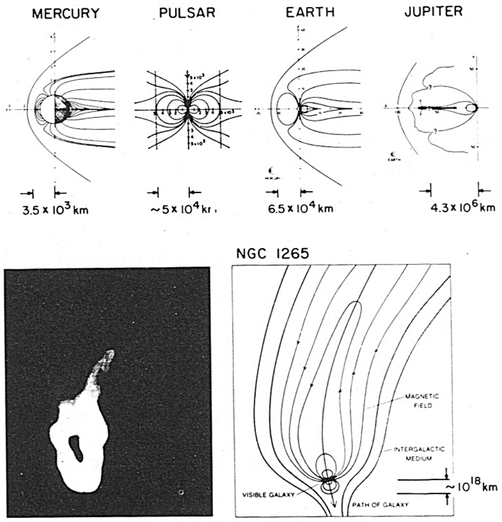


Figure 9. Geospace-like magnetosphere systems are probably common throughout the universe even though their scale sizes vary over an enormous range. For example, the subsolar magnetopause distance for Mercury is 3.5×10^3 km; for the radio galaxy NGC 1265 the analagous distance is roughly 10^{18}!

ACKNOWLEDGEMENT

I gratefully acknowledge the two years of exceptional effort given by the Science Definition Working Group, and especially my Co-Chairman, J. K. Alexander. Members of the group were:

Co-Chairman	J. K. Alexander	Goddard Space Flight Center
	H. S. Bridge	Massachusetts Institute of Technology
	J. L. Burch	Southwest Research Institute
	L. F. Burlaga	Goddard Space Flight Center
	D. P. Cauffman	Lockheed Palo Alto Research Laboratory
	F. V. Coroniti	University of California, Los Angeles
	W. C. Feldman	Los Alamos Scientific Laboratory
	L. A. Frank	University of Iowa
	T. A. Fritz	NOAA Space Environment Laboratory
	J. Geiss	University of Bern, Switzerland
	G. Gloeckler	University of Maryland
	G. Haerendel	Max-Planck Institute, Astrophysics
	R. E. Hartle	Goddard Space Flight Center
	R. G. Johnson	Lockheed Palo Alto Research Laboratory
	S. M. Krimigis	JHU, Applied Physics Laboratory
	L. R. Lyons	NOAA Space Environment Laboratory
	A. Nishida	University of Tokyo
	B. Whalen	National Research Council of Canada
Co-Chairman	D. J. Williams	NOAA Space Environment Laboratory

I also wish to acknowledge the many individuals who provided valuable contributions in the form of suggestions, ideas, information and hard work during the course of this study, especially S.-I. Akasofu, R. W. Farquhar, W. D. Hibbard, T. W. Hill, B. C. Holland, D. Hovestadt, C. E. McIlwain, D. P. Muhonen, N. F. Ness, G. P. Newton, G. A. Paulikas, G. T. Roach, E. R. Schmerling, D. P. Stern, A. F. Timothy, D. D. Wallis and J. D. Winningham. I particularly wish to thank K. Papadopoulos for his invaluable contributions to the program.

REFERENCES

1. Origin of Plasmas in the Earth's Neighborhood. Final Report of the NASA Science Definition Working Group, Co-Chairmen J. K. Alexander and D. J. Williams: April 1979.

2. Space Plasma Physics: The Study of Solar-System Plasmas. Vols. I & II; Space Science Board. A. G. W. Cameron, Chairman (S. A. Colgate, Study Chairman): National Academy of Sciences, Washington, D.C.: 1978.

3. "The Significance of Magnetospheric Research for Progress in Astrophysics"; C.-G. Fälthammar. S.-I. Akasofu and H. Alfvén, Nature, 275, 185: 1978.

4. Measures for Progress: A History of the National Bureau of Standards. Rexmond C. Cochrane, U. S. Department of Commerce: 1966.

5. Watch Upon A Star: A Description of Space Environment Services. NOAA PA 77002, U. S. Department of Commerce: 1977.