

GEM

Geospace Environment Modeling

**A PROGRAM OF
SOLAR-TERRESTRIAL RESEARCH IN GLOBAL GEOSCIENCES**

Prepared for

**The Magnetospheric Physics Program
of the
Upper Atmosphere Research Section
Division of Atmospheric Sciences
National Science Foundation**

by the

GEM Steering Committee

May 1988

Foreword

The medium physically tied to Planet Earth extends hundreds of thousands of kilometers into space. The outer envelope of the earth system is strongly controlled by the variable components of solar energy, and its study is an important part of the relatively new discipline called Solar-Terrestrial Research.

In September 1986, under the initiative of the undersigned, a group of scientists (*) made a presentation to NSF Director Erich Bloch and Assistant Director William Merrell in which they proposed that aspects of solar-terrestrial research relevant to the total earth system be incorporated as integral components of the Global Geosciences Program of NSF.

Encouraged by Dr. Merrell, a proposal was submitted to the Division of Atmospheric Sciences seeking support for the organization of a consultative process in which consensus views would be sought for the formulation of a modest, yet innovative program of solar-terrestrial research within the framework of the Global Geosciences initiative. This consultative process would have as its central focus a Workshop to be held with the purpose of (1) examining the current status of solar-terrestrial research; (2) identifying new initiatives within given budget increment projections; and (3) formulating pertinent recommendations and a comprehensive plan.

The proposal was funded by the Solar-Terrestrial Program of the Division of Atmospheric Sciences, with the undersigned as the principal investigator. The Workshop took place in Seattle on August 6-8, 1987, at the University of Washington. Rough drafts of recommended projects were prepared during the Workshop and further refined in two subsequent meetings by the Steering Committee and the Segment Coordinators (**). Valuable comments and suggestions were received from members of the Committee on Solar-Terrestrial Research of the NAS/NRC Board of Atmospheric Sciences and Climate.

I sincerely hope that this Report indeed does represent a consensus view of the Workshop participants, a view which, necessarily, can only be a "least square fit" to the sometimes diverging opinions or wishes formulated during the discussions. I also hope that the planning process that started with the Seattle Workshop will become an ongoing part of the organizational activity of solar-terrestrial research in the United States.

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Fairbanks, May 1988

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Geospace Environment Modeling (GEM)

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Geospace Environment Modeling (GEM)

EXECUTIVE SUMMARY

As humans extend their frontiers beyond the surface of their home planet—moving technological systems, observatories and colonies into space—accurate predictions of “weather and climate in space” become increasingly important. New scientific data and theoretical models are required to achieve this predictive capability. Therefore, a major new research initiative is proposed entitled **Geospace Environment Modeling (GEM)**. The implementation of this initiative is envisaged for the period 1990-1995, with a possible extension to the end of the decade.

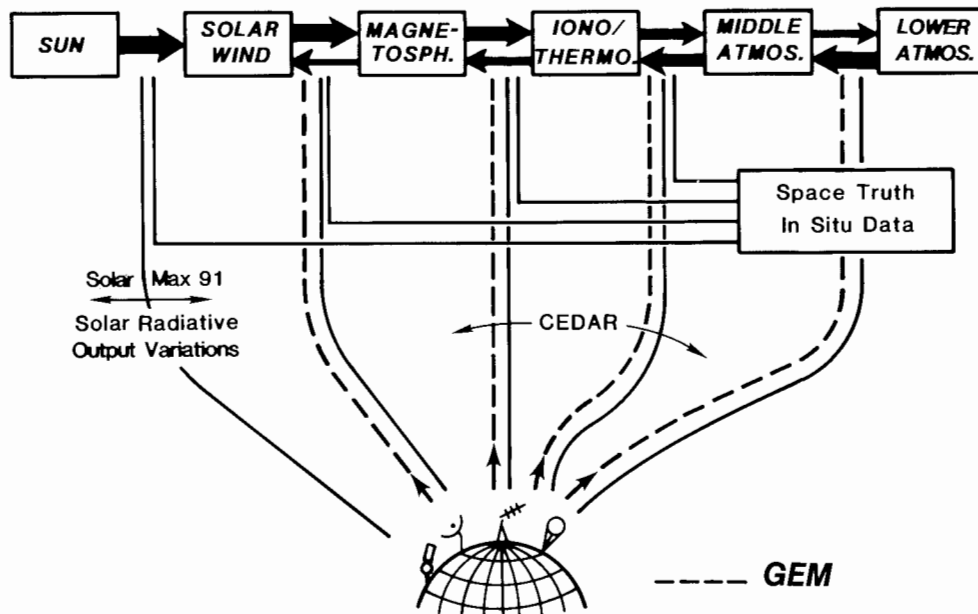
The scientific goal of GEM is to understand the solar-terrestrial system well enough to be able to formulate a mathematical framework that can predict the deterministic properties of geospace (“weather in space”) and the statistical characteristics of its stochastic properties (“climate in space”).

The operational goal of GEM is to stimulate innovative coordinated, yet independent theoretical and experimental approaches toward the solution of a common set of well-defined problems related to the understanding of physical processes in geospace.

The main predictive focus of GEM will be centered on “geospace”, defined for this program as that region of space above the aerodynamically navigable atmosphere, in which the medium is gravitationally and magnetically tied to Planet Earth.

A major impediment at present to the quantitative understanding of geospace and to the formulation of models for predictive purposes is the existence of three major scientific problems: 1. A lack of understanding of global structural and transport properties of the outer boundary regions of the magnetosphere; 2. A lack of understanding of the dynamics of the magnetotail as an active component of geospace; 3. A lack of understanding of the coupling of geospace plasma to the neutral atmosphere and the downward (and upward) propagation of energy and chemical species.

The GEM initiative is designed to address these problems. It will have three major components: (1) Theory and Model Development; (2) Observations and Measurements; and (3) Data and Information Systems. While this subdivision is traditional, the proposed contents of each program element and their interrelations are not.



**Remote Sensing from Ground and Balloons
Simulation and Modeling Data Analysis**

Figure 1: The solar-terrestrial chain of interacting regions: principal areas of involvement of the Geospace Environment Modeling program in relation to other existing or proposed NSF programs.

Funding for the GEM program would be derived from yearly increments above an inflation-corrected budget baseline of the Solar-Terrestrial Program of the NSF Division of Atmospheric Sciences. In no way should the proposed initiative burden the traditional research grant funding mode, whose continuity is judged to be an essential element for the future success of NSF-supported solar-terrestrial science. Moreover, GEM should build upon and complement the studies carried out in the traditional mode.

In addition, the GEM initiative should not compete with other simultaneously-planned new NSF initiatives such as the Coupling, Energetics and Dynamics of Atmospheric Regions program (CEDAR) and the program Solar Flare Research at the next Solar Maximum (MAX 91) but, rather, be designed to synergistically complement them. On the other hand, GEM should be carefully coordinated with selected major national and international programs, such as key U.S. satellite missions, the NASA/ESA/ISAS International Solar-Terrestrial Program, and SCOSTEP's Solar-Terrestrial Energy Program.

The coordination of NSF-supported activities in geospace simulation and modeling, remote sensing of geospace from the ground and from balloon-borne platforms, and state-of-the-art electronic data handling systems will be the touchstone of GEM. **Figure 1** shows the principal areas of involvement of the program in relation to the solar-terrestrial regions and their interactions, and in relation to other major coordinated research programs.

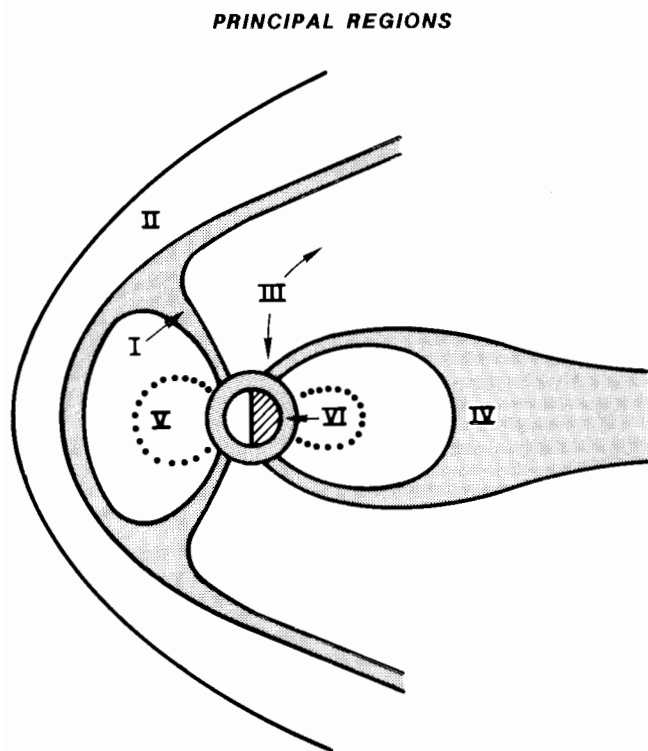


Figure 2: Principal regions of geospace to be investigated by GEM. I: Magnetopause, boundary layer and cusp; II: Magnetosheath; III: Polar cap and magnetotail; IV: Plasma sheet and substorm region; V: Plasmasphere; VI: Middle atmosphere.

The principal regions of geospace to be intensely investigated in GEM are depicted in **Figure 2**. The principal theoretical and experimental activities proposed for GEM are shown in **Figure 3**. The major recommendations regarding these program components are summarized below.

THEORY AND MODEL DEVELOPMENT

We recommend that NSF support a sequence of **Theory Campaigns (TC)** directed toward the solution of specific unanswered questions concerning the geospace environment. A Theory Campaign is defined as a (typically) three-year effort by several independent research groups, working simultaneously but following different approaches, to address a common, preselected problem, and utilizing where possible the national resource of available ground-based and space-based data. A TC would also involve workshops to assess progress and discuss the future course of the Campaign.

The following TC's are recommended in a temporally ordered sequence:

1. **Magnetopause and Boundary Layer Physics.** A concerted effort to produce quantitative information about the important plasma and energy transport processes at the magnetopause.
2. **Model of the Magnetosheath.** Develop an accurate user-friendly numerical model of the magnetic field, velocity, pressure and density of the plasma flow just outside the magnetopause, for given solar wind conditions.
3. **Global Modeling of the Magnetospheric B-Field.** Develop an accurate, versatile, large-scale field model that includes the consequences of all major current systems, for different levels of geomagnetic activity.
4. **Magnetotail and Substorms.** Develop a three-dimensional code for tail reconnection; develop the theory and simulation of waves in inhomogeneous media; study the formation and acceleration of plasmoids; determine the influence of the magnetotail on, or its response to, substorm dynamics.
5. **Convection and Coupling.** Study the generation and propagation of field-aligned currents and electric fields, the influence of ionospheric conductivity on convection, and the relationship between the boundary layer flow and ionospheric conditions.
6. **Global Plasma Model.** Develop a model of geospace plasma that includes sources, energization, transport, and sinks of particles at all energies. As a final stage in the theory component of the GEM initiative, comprehensive **general circulation models** for geospace will be developed.

No Theory Campaign is being proposed at this time for the study of the important and intriguing aspects of geospace interactions with the neutral atmosphere and of the electrical state in the lower atmosphere and its coupling to geospace phenomena (**Figure 4**). This does not preclude the possibility that a TC might be proposed at a later stage of GEM in collaboration with the CEDAR program to provide direction to the observational campaign on Magnetosphere-Atmosphere Electrodynamics Coupling (see 4. below).

OBSERVATIONS AND MEASUREMENTS

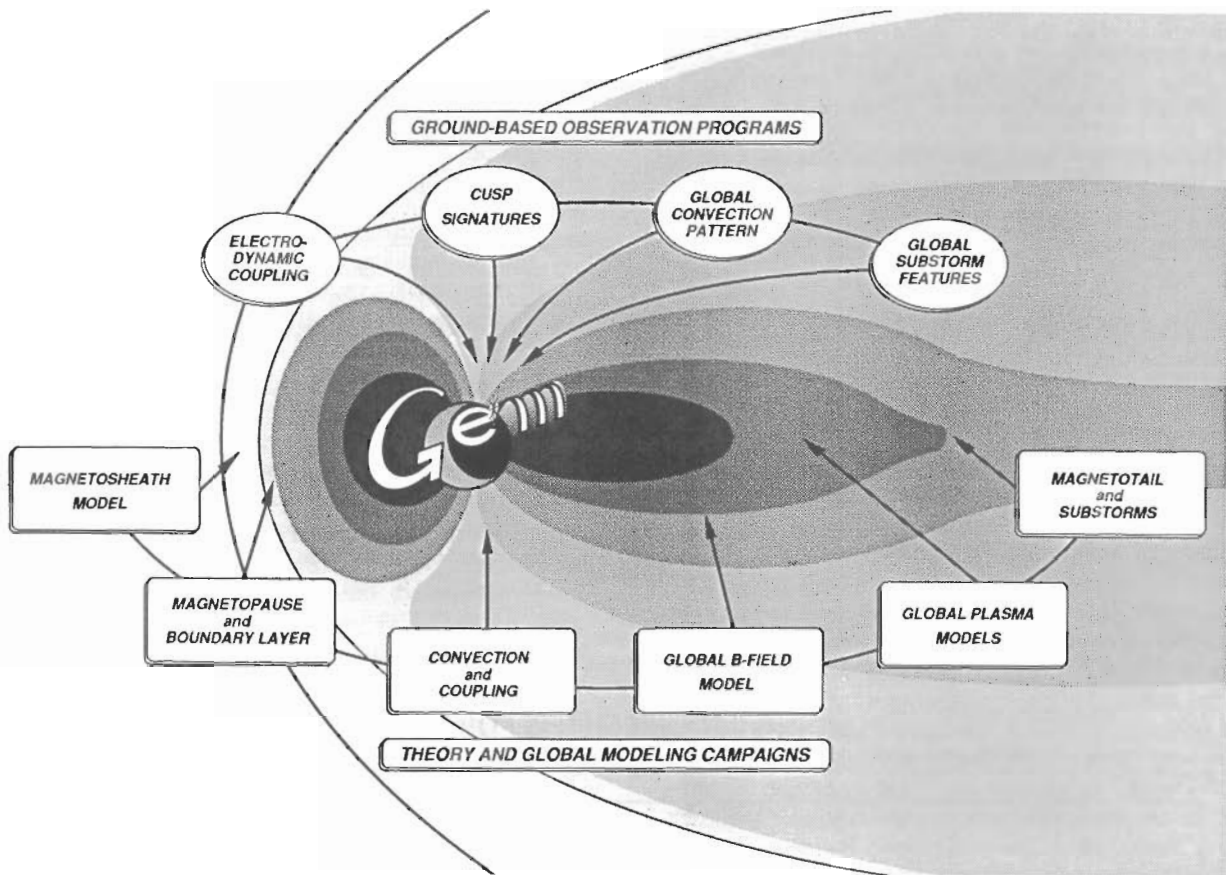
The theoretical topics outlined above point the way toward formulating observational and measurement programs required to achieve the predictive goal of GEM. These experimental programs are divided into two groups.

The first group includes programs aimed at: (i) Understanding the connections between energy and mass transfer processes in the outer confines of geospace and their manifestations in the ionosphere; (ii) Understanding better the roles of the magnetotail and the ionosphere in substorm dynamics; and (iii) Obtaining the global convection pattern in the polar caps and auroral zone with a time-resolution of a few minutes. These programs are most directly related to the Theory Campaigns described above.

The second group will focus on global electrodynamic interactions between the magnetosphere, middle atmosphere and the lower atmosphere, concentrating on the vertical coupling between about 40 and about 100 km.

Four major coordinated Observing Campaigns (OC) are recommended:

1. **Ionosphere Signatures of Magnetospheric Cusp Processes.** A study with high time-resolution, adequate spatial extension and continuity of the manifestations of cusp processes in the ionosphere, using a variety of optical, magnetic and radio instruments, comprising project GAMBLE [Ground-Airborne Magnetic Boundary Layer Experiment] in the region of Svalbard, complemented with measurements at other locations.
2. **Global Substorm Features.** The establishment of a longitudinal chain of magnetometers appropriately located to determine the gross features of ionospheric and field-aligned currents and to provide essential information on the timing and location of substorms.
3. **Global Convection Pattern.** Improve the understanding of magnetospheric and ionospheric response to changing solar wind conditions by observing with a variety of radar and ionosonde techniques the convection pattern, mass transport and cross-polar cap potential difference with improved temporal and spatial resolution and for continuous periods of several hours each.



GEOSPACE ENVIRONMENT MODELING

Figure 3: Summary view of major theoretical and experimental program components of GEM.

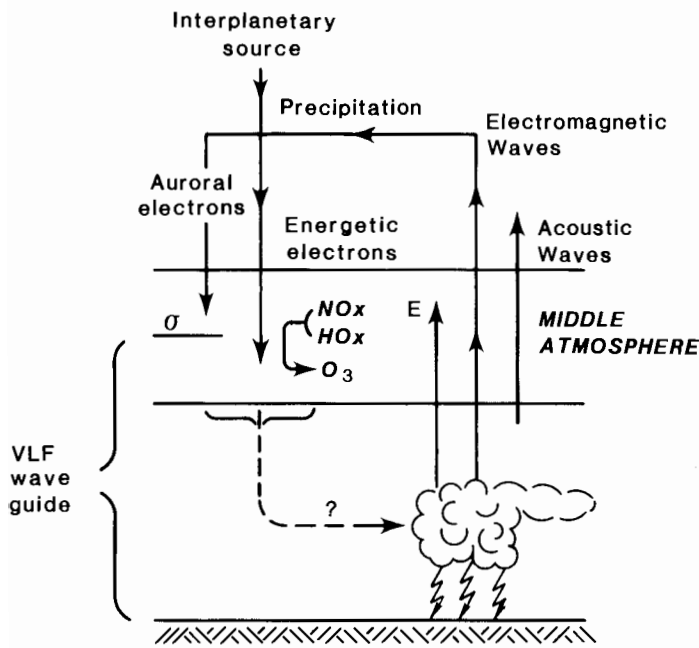


Figure 4: Interactions between geospace and the neutral atmosphere, and effects of the electrical state in the lower atmosphere on geospace above.

4. **Magnetosphere-Atmosphere Electrodynamic Coupling.** The establishment of a network of electric and magnetic field detectors in the 1-100 Hz band for the continuous monitoring of lightning bursts in order to provide global imaging of D-region conductivity; the use of a VLF network for the study of wave-induced particle precipitation on a world-wide scale; and long-duration balloon measurements of electric field and conductivity.

No Observing Campaign is being proposed at the present time as a correlative to the Global Plasma Model TC. An experimental ground-based program specifically focused on the study of the polar ionosphere as a source of magnetospheric ions may well be incorporated into GEM at a later stage.

DATA ANALYSIS AND INFORMATION SYSTEMS

The third component of GEM consists of the application of modern data-handling techniques and strategies to existing and new solar-terrestrial data. The following initiatives are proposed:

1. **Discipline Data Centers (DDC).** Establish national repositories of specialized data at universities or laboratories, with greatly expanded capabilities, including catalogs and directories, quality checks, standardized formats, assistance to users, data and information dissemination and electronic communication. "Problem-oriented" DDCs will be associated with specific Theory Campaigns and would serve as a mechanism to bring together theoreticians and experimentalists. "Data-oriented" DDCs would serve a general purpose.
2. **Electronic Communications.** Use NSF-Net as the cornerstone for communications of the GEM program, especially to make major capabilities and facilities accessible to researchers at institutions that may be resource-limited.
3. **New Technology.** Test and evaluate new technologies to optimize the use of solar-terrestrial data by establishing means for easy access to data, more efficient data use, and improved visualization techniques for GEM researchers.
4. **Supercomputing Resources.** Take full advantage of the resources to be made available as part of the NSF Supercomputing Initiative.
5. **Education.** Increase the awareness of solar-terrestrial research to students early in their educational career by making selected data bases on floppy disks available to schools, and encouraging and supporting GEM scientists to speak to such student groups and kindle their interest in solar-terrestrial phenomena with hands-on event analyses.

BUDGET

Table 1 presents an outline of the funding requirements for GEM. It is important to note that *all budget figures given in this report are strawman estimates*. Detailed budgets will be prepared and proposed by the GEM Steering Committee on the basis of further planning and technical workshops.

TABLE 1

FUNDING REQUIREMENTS FOR GEM (IN K\$)

| | '91 | '92 | '93 | '94 | '95 | '96 |
|---------------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Theory and Model Development | 700 | 1750 | 2700 | 2500 | 3050 | 2800 |
| Observations and Measurements | 1000 | 1900 | 2000 | 2870 | 2770 | 2620 |
| Data Analysis and Information Systems | 400 | 600 | 800 | 1350 | 1400 | 2250 |
| TOTAL | 2100 | 4250 | 5500 | 6720 | 7220 | 7670 |

CHAPTER I:

Toward Geospace Environment Modeling (GEM)

1.1 Relevance of Solar-Terrestrial Research to NSF's Global Geosciences Program

Shortly after the beginning of the "space age" with the launching of the first man-made object into terrestrial orbit, geospace assumed a fundamental role as a technological resource for all countries, advanced and developing alike. Today satellite systems for communications, weather prediction, navigation and remote sensing of natural resources are supporting in an essential way many facets of societal operations. We must expect that this trend will continue; for instance, in perhaps less than three decades trans-atmospheric transportation will be routine and satellite systems will sustain human colonies in space.

The medium in which earth-orbiting systems operate is hostile. Far from a perfect vacuum, it is made up of high-temperature gas and corpuscular radiation of varying densities and intensities; these solar-activity controlled variations can reach proportions dangerous to orbital stability, to electronic systems performance, to shuttle and spaceplane re-entry, and to the life of humans in orbit. Dramatic examples of solar-activity induced satellite failures are the unexpected early degradation of the orbit of Skylab due to unusual upper atmosphere heating, and the demise of satellite GOES-5, most probably caused by a large injection of energetic electrons from the outer magnetosphere. The need to predict "weather and climate" in geospace is becoming as important as the need to predict weather and climate in the inhospitable regions on Earth into which industrial activity has moved during the last decades, such as the Arctic and some of the arid lands.

The study of geospace is part of a new science that emerged three decades ago, called Solar-Terrestrial Research (STR). This science can be defined as the study of the generation, flow and dissipation of energy and the transfer of mass in the solar-terrestrial system [the chain of coupled regions extending from the solar photosphere to the Earth's upper atmosphere], including the relevant physical and chemical interaction mechanisms, and the effects on the proximate terrestrial environment.

By its very nature, STR is firmly rooted in astrophysics at the "upper end", in atmospheric physics and chemistry at the "lower end", and in space physics in between. Its repertoire of observational techniques includes in situ space and upper atmosphere measurements with spacecraft, rockets and balloons; in situ ground-based measurements; and remote sensing from ground up and from space down. Theoretical approaches include analytical studies in plasma physics and wave propagation, non-linear dynamics, numerical modeling and simulation. As a scientific field with a clearly defined identity and objectives and a large and cohesive constituency of researchers, STR is not a branch of the atmospheric sciences, not a branch of astrophysics, and not a branch of space science—rather, it is a synergistic fusion of elements drawn from each one of these three separate disciplines.

Recent studies and national and international program proposals have formulated broad objectives for STR during the next 10-15 years (e.g., NASA/ESA/ISAS, 1984; NAS/NRC, 1984a and 1985; SCOSTEP, 1986a). From these studies, the multidisciplinary nature of STR and the need for a global approach to the study of the solar-terrestrial system emerge quite clearly. So do the many potential benefits that science and society can expect from such an integrated study.

There are several aspects of STR that belong naturally into NSF's Global Geosciences (NSF, 1987) program. The CEDAR project (NSF, 1986) is one important example that is already a part of this program. The present document is a proposal for another balanced, well-coordinated program of enhanced research to be supported by the Atmospheric Sciences Division of NSF during fiscal years 1990-1995. The pertinent recommendations are based on a Workshop held in Seattle on August 5-8, 1987, with input from over 70 members of the STR community.

The proposed name for the new program is **Geospace Environment Modeling (GEM)**; its major aims, components and pertinent recommendations are described in the following chapters.

1.2 The Evolution of Solar-Terrestrial Science

Solar-terrestrial research has attained a point in its evolution where it needs a higher level of research organization. Already it has passed through several stages of maturation, and now it stands ready to start a major new phase.

With the International Geophysical Year in 1957/58 and the advent of satellite data, STR became a major scientific discipline. The first decade of the "space era" saw the new field explore the distinct compartments of space, which led to important discoveries about the solar wind, the magnetosphere, and the ionosphere. In this first phase, each compartment formed a subdiscipline. The first theories were correspondingly parochial.

The late 1960's ushered in a second phase, as a movement to integrate the new science began when researchers realized how thoroughly the magnetic field in the solar wind regulates magnetospheric behavior. A new concept—solar wind-magnetosphere coupling—grew to major importance. From a picture of territorial subfields separated by discipline fences, the conceptual level rose to give a view of linked domains—the "solar-terrestrial chain"—extending from the solar corona to the ionosphere. As in the traditional view of "Solar-Terrestrial Relations", causality moved through the links unidirectionally from the sun to the earth.

The onset of the third phase of STR, during the 1970's, was marked by another rise in the conceptual level, when researchers recognized that the coupling between the magnetosphere and ionosphere was electrical, and therefore two-way, interactive. The last link in the solar-terrestrial chain was replaced by a feedback loop, which ensured that

electrical currents leaving and entering the magnetosphere self-consistently matched currents entering and leaving the ionosphere. Research at this new, more complex level needed computer modeling. In the ensuing decade, ending with the present, numerical codes to model and simulate interactive magnetosphere-ionosphere coupling grew sophisticated.

We have now reached the fourth phase. It begins with the realization that, since the solar wind-magnetosphere-ionosphere system reveals itself to be almost completely interactively coupled, it must be viewed as a unit. Because we cannot see the unit and watch it work as we can distant astrophysical objects, this realization has dawned slowly, by studying the separate parts and finding them connected and interdependent. In this fourth phase, the neutral atmosphere begins to play an increasingly important role as the last interactive link of the solar-terrestrial chain. From what we know already, it is clear that a model having all of the main components interactively coupled is closer to reality than the old model which had the components linked together serially. In the new model causality operates in feed-back loops to determine the system's integral response to solar variability.

A discipline that is responsible for bringing a complicated, compound, fully interactive system into the sphere of understanding must conduct its research very systematically. Because it has a clearly defined ultimate goal, such a discipline has a mission. Because its purview comprises a limited number of components and a circumscribed, albeit possibly huge, domain of activity, such a discipline can design a finite strategy to reach its goal, in principle. This mode characterizes the new phase of solar-terrestrial research.

The new mode does not supplant the old. Research must continue to elucidate how the separate components work, clarify the physics of local processes, and make discoveries pertaining to one place or another and one region or another. However, to gather, organize, analyze and interpret data on global interactive behavior, and to build the complex theoretical structures and models needed to test our understanding of this behavior, will require the new level of organization cited above.

1.3 Lessons from Atmospheric Science for the Formulation of GEM

Atmospheric science has evolved through similar stages, and its lessons are useful. The atmosphere and the geospace environment both exhibit global connection (energy flow from equator to pole versus energy flow from solar wind to ionosphere), non-local coupling ("teleconnection" in meteorology versus field-aligned current systems in the magnetosphere), bimodal dynamics (zonal and blocked systems in meteorology versus continuously and explosively driven processes in the substorm). Both environments contain multiple components engaged in complex nonlinear interactions.

To deal with this level of global interconnection, physical complexity, and dynamical nonlinearity, atmospheric scientists have developed elaborate computer codes called general circulation models (GCMs). They aim at simulating the

dynamics of the atmosphere as a whole. Their domain comprises all latitudes and longitudes, and altitudes from the surface to the stratopause. Because the equations that describe atmospheric motion are known and the physics behind the sources and sinks of energy and momentum are known well enough to parameterize, GCM simulations exhibit the behavior that characterizes the atmosphere's multi-component nonlinear interactions. On the one hand, GCMs test understanding through the accuracy of their simulations. On the other hand, they reveal phenomena that give new insights into atmospheric behavior. They are used in numerical weather forecasting and in research, for example, to predict the climatic consequences of changes in atmospheric composition. GCM development represents the response of atmospheric science to deal with the problem of the global interconnectedness of the atmosphere.

The ultimate goal of STR is to understand the physics and the chemistry of the solar-terrestrial system well enough to be able to formulate a mathematical framework that predicts the deterministic properties of the system ("weather in space") and the statistical characteristics of its stochastic properties ("climate in space"). Parallel problems with atmospheric science thus suggest that solar-terrestrial science achieve its long-term goal, conceptually if not practically, by GCMs—more specifically, by developing a geospace environment GCM. We will call research aimed at achieving this goal "Geospace Environment Modeling" (GEM).

Aside from benefiting from the experience of atmospheric science, there are other important reasons to adopt GEM as the specific goal to implement the new phase of STR: 1. It unifies the discipline by giving it a concrete common goal. 2. It provides a goal that is high and broad enough to include its constituency's present projects and ambitions. 3. GEM sets an order by which to organize, prioritize, and justify the discipline's efforts. 4. It gives the field a mission that can be recognized as being (a) intellectually the most challenging (because it is comprehensive and entails the need to design a discipline-wide research strategy); (b) practically the most useful (because of its power to test global concepts, reveal new behavior, and provide space weather forecasts); and (c) organizationally the most beneficial for the discipline (because it incorporates theoretical, experimental and data-handling activities, relates them to each other, and gives them a common direction).

The maturity of solar-terrestrial science can be measured by how close it has approached the goal as just defined. Reaching it entails evolving through a formulation stage and an implementation stage. Regarding global circulation, STR has evolved to the implementation stage for only a near-earth portion of its domain. Three major problems at the formulation stage block the transition to the implementation stage with a global model for the geospace environment. One of these is a lack of understanding of the global architecture and the transport properties of the magnetospheric boundary. Without this, solar-terrestrial scientists cannot code the computer to describe how the solar wind couples to the magnetosphere. The second is a lack of understanding of the dynamics of the magnetosphere-magnetotail system. Since magnetospheric circulation passes through the tail, and the most dynamical magnetospheric "weather"

system—the substorm—is associated with the tail, solar-terrestrial science cannot implement a global circulation model before the tail component of the circulation is understood well enough to formulate it mathematically. The third problem is related to the lack of understanding of the coupling of geospace plasma to the neutral atmosphere and the downward as well as upward propagation of energy and chemical species.

In addition to these formulation problems, a number of well-defined implementation problems are clearly seen once GEM becomes a goal of STR. Once all these problems are brought to a satisfactory stage of development, there is the final assembly stage—the fusion of the results into a comprehensive, global geospace GCM.

1.4 Roles of Complementary Programs

The fourth phase of solar-terrestrial science began already with the planning of the International Solar-Terrestrial Physics program (ISTP). ISTP builds around a multi-spacecraft mission. It involves NASA and the space agencies of Japan and Europe (NASA/ESA/ISAS, 1984; IACG, 1986). With satellites in strategic orbits making in situ and remote sensing observations, ISTP will gather simultaneous data on the major, spatially distinct components of the geospace system. It seeks to coordinate the measurements to follow the flow of energy and mass through the geospace environment.

Also, the discipline has attacked problems of global dynamics through Coordinated Data Analysis Workshops (CDAWs) that emerged as a product of the International Magnetospheric Study (IMS) (ESA, 1984). CDAWs focus on important aspects of major problems. The latest one studied the roles plasmoids and boundary layers play in substorms. Exhaustively searching the logs of spacecraft and ground stations, CDAWs look for good examples of the chosen process when data exist to interrogate the important aspects. This approach provides the best “metamission” organization of data sets for case studies of global phenomena.

Another example of phase-four-type STR coordination was Project PROMIS (Polar Region and Outer Magnetosphere International Study) which gathered and coordinated data from six spacecraft for three months in 1986, when their orbits favored synoptic studies. Conceptually, a project like PROMIS lies between CDAWs, which scavenge old data files for global coincidences, and ISTP, which will put spacecraft in orbits chosen to optimize global studies. Like CDAWs, PROMIS launched no new spacecraft. Like ISTP, it planned the observations in advance.

In the framework of these discipline-wide data gathering and analyzing projects, GEM will add new, essential data. With its view of a common goal, it will prescribe a higher level of research organization to define, arrange, and order individual projects and campaigns. The data gathering component of GEM's program comprises ground-based observations of the auroral oval and the polar cap. To the data other projects gather, GEM will add regional and global maps of processes which, like magnetospheric convection, project images of themselves magnetically onto the ionosphere. GEM's observations will trace, measure, and follow

the important field-aligned currents that unite the magnetosphere with the ionosphere and make it internally interactive. Paired and synchronized with the observing program, GEM's theory program is planned as a phased series of “theory campaigns.” The theory program will marshal the discipline to focus on one common objective and then another, each preparing the next, and all forming steps leading to GEM's stated goal.

As programs and projects that emphasize the use of data gathered by spacecraft, ISTP, the CDAWs, and PROMIS naturally have their institutional base in the U.S. within the Space Physics Division of NASA. With its emphasis on ground-based data and a goal that views solar-terrestrial research as an environmental science, the GEM program has its natural institutional base in the Upper Atmosphere Research Section of the Division of Atmospheric Sciences of NSF. As a program that will benefit from, and in many aspects require, international cooperation, GEM will be a natural component of the U.S. contribution to the Solar-Terrestrial Energy Program (STEP), currently being planned by the ICSU Scientific Committee on Solar-Terrestrial Physics (SCOSTEP, 1986 a and b).

Finally, it is of crucial importance that GEM be planned and carried out in close coordination with the other major solar-terrestrial science program of NSF, namely Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR). This program, which already has been incorporated into NSF's Global Geosciences initiative, is focused on the study of aeronomic processes and thus synergistically complements the plasma, field and modeling focus of GEM. The need for close coordination between GEM and CEDAR is warranted to minimize the competition for financial resources, and many scientists who would be expected to become participants in GEM are already committed to projects that pertain to CEDAR.

1.5 The GEM Program

Structurally the GEM program will consist of an overlapping series of theory campaigns synchronized with a complementary overlapping series of observing campaigns. Adequate data and information systems will be established concurrently. Table 2 outlines the program.

The program is an agenda to move the discipline through the stages identified in the Table. It optimizes the use of information gained at each stage. Each campaign lasts approximately three years, and a new campaign begins each year. A three year ramp beginning in 1990 reaches a plateau in 1992, after which starting campaigns replace ending ones. Because solar-terrestrial science is young and vigorous, we anticipate that GEM will continue through and beyond 1996 at a steady level of three paired campaigns operating concurrently each year.

As the *sine qua non* of geospace modeling, solar wind coupling stands first in the list of campaigns. Theorists view it as a problem in boundary structure and dynamics. To ground-based observers it is a problem of reading the ionospheric signatures that boundary processes inscribe in polar cusp plasma. Because it is a key problem, and because sustained, partially coordinated efforts to solve it have prepared needed data and theoretical tools, and also because

TABLE 2

GEM PROGRAM OUTLINE

| | '91 | '92 | '93 | '94 | '95 | '96 | '97 | '98 | '99 | '00 |
|------------------------------------|---------------------------------|-------------------------|------------------------|-----------------------|--------------------------|--|-----|-----|-----|-----|
| THEORY CAMPAIGNS | Magnetopause and Boundary Layer | | | | | | | | | |
| | | Model of Magnetosheath | | | | | | | | |
| | | | Global B-Field | | | | | | | |
| | | | Magnetotail & Substorm | | | | | | | |
| | | | | Convection & Coupling | | | | | | |
| | | | | | Global Plasma Model | | | | | |
| | | | | | | Magnetospheric General Circulation Model | | | | |
| OBSERVING CAMPAIGNS | Cusp Signatures | | | | | | | | | |
| | | Substorm Features | | | | | | | | |
| | | | Convection | | | | | | | |
| | | | | | Electro-dynamic Coupling | | | | | |
| DATA AND INFORMATION SYSTEMS | Cusp DDC* | | | | | | | | | |
| | | Magnetosphere Model DDC | | | | | | | | |
| | | | Substorm DDC | | | | | | | |
| | | | | Convection DDC | | | | | | |
| | | | | | Plasma DDC | | | | | |
| | *Discipline Data Center | | | | | | | | | |

much planning has already gone into designing an observing campaign, the community is poised to respond to the signal from GEM to concentrate its forces in a focused attack on this problem.

A year after the attack on the solar wind coupling problem begins, the theory component of GEM launches two campaigns. One will build models to project upstream solar

wind conditions through the bow shock and magnetosheath to predict the condition of the environment that contacts the magnetosphere. These models are needed to provide inputs to the solar wind coupling campaign. The other theory campaign will build models to project processes and features magnetically from place to place within the magnetosphere. These models are needed to map the signatures of boundary

and tail processes to the ionosphere.

The next pair of closely coordinated theory and observing campaigns aims at solving the second formulation problem: How does magnetospheric circulation cycle through the tail? As an eddy created by a shear in a flow profoundly affects the flow, the tail, created by the circulation, profoundly affects the circulation. Against this critical problem, magnetospheric science has amassed an arsenal of data, models, and campaigns. GEM will incorporate these, supplement them with high resolution, comprehensive synoptic data on the midnight sectors of the polar cap and auroral oval, and activate a regiment of theorists to train the powers of analytical and computer modeling on the problem. To test the magnetic field models, the second Observing Campaign will also measure and compare magnetospheric signatures simultaneously in the northern and southern hemispheres.

After campaigns to learn how the solar wind starts magnetospheric circulation and carries it tailward, and campaigns to learn what happens in the tail to reverse the circulation and send it sunward, there follows a pair of campaigns to determine the complete patterns of global circulation for different solar wind conditions. Here theorists shift from studying the boundary by itself and the tail by itself to considering their complementary roles as opposing regulators of the circulation. In the presence of distortions produced by reactive magnetospheric currents and modulations imposed by interactive coupling to the ionosphere, theory must convert the pattern any solar wind would inscribe to the one realized after the magnetosphere and ionosphere react. For their part, observers must deploy their instruments to make high resolution “movie pictures” that show the whole ionospheric image of magnetospheric circulation moving, expanding, pulsing, contracting, and relaxing between states of agitation and quiescence.

The next set of campaigns decouples theory and ground-based observing to send each on separate important projects. Theorists will build transport and dynamic equilibrium models of the magnetospheric particle populations, emphasizing the ionosphere as a source. Like the magnetosheath and magnetic modeling campaigns, this project will form an essential part of geospace environmental modeling. On the other hand, for the first time, observers will measure and chart in a systematic and coordinated way the electrodynamic coupling between the ionosphere and the lower atmospheric layers. By systematically investigating the solar-terrestrial influence on lower atmospheric processes, the campaign will provide the best data—scientifically valuable in themselves—to evaluate this long-standing, controversial subject.

These complete the core campaigns envisioned in the baseline GEM program to enable the discipline to assemble the first geospace GCM. Thus, the last set of activity in the baseline program calls for theorists to effect the assembly and for observers to test it.

1.6 Outline of the Report

While observing campaigns are familiar to the field, theory campaigns are novel. The next section defines this new concept and its use in the GEM program. The section goes on to describe each of the theory campaigns in the baseline GEM program as outlined above. The following section describes each of the observing campaigns, which are matched to the theory campaigns except for Electrodynamical Coupling. The final section presents a plan for innovative data analysis and information systems.

CHAPTER II: Theory and Model Development

2.1 A New Concept: Theory Campaigns

The implementation of the ambitious GEM initiative requires a novel strategy which draws on the substantial expertise of the community of theorists and modelers and also involves synergistically the community of experimentalists. This approach should guarantee the flexibility and long-term viability of the GEM research initiative and facilitate the participation of knowledgeable outsiders. We therefore suggest that NSF support a sequence of **theory campaigns** (TC) directed towards the solution of specific unanswered questions concerning the geospace environment.

We envisage each TC to involve the concentration of new NSF resources for a limited time. The resources would be used to support several independent research groups selected by peer review, all working towards the solution of the scientific questions formulated in the announcement of the particular TC. Each group would use a different approach (e.g., MHD modeling, analytic theory, kinetic simulation) to the solution of critical problems. In addition, some resources would be used to conduct workshops during which the participating groups would examine the results obtained thus far and discuss problems that must be resolved to permit further progress. In order to guarantee the relevance of the TCs, to other current research, groups funded in each TC would be strongly encouraged to utilize the national resources of existing and incoming spacecraft and ground-based observations.

For the duration of the campaign, typically three years, the participating groups would be provided with the funding and organizational structure needed to assure that all suitable theoretical and observational knowledge and expertise are brought to bear on the problems.

At the end of each TC an assessment would be made of the problem area and the progress made during the campaign. Based on the outcome of this assessment, it could then be decided to what extent and at what level campaign-mode funding should be continued and for what approaches such funding would be appropriate.

In order to achieve the goals outlined above and in order to assure that the campaigns are maximally effective and of high scientific quality, the following set of procedures is recommended.

Formulation Phase

Before the announcement of each campaign, a workshop will be held to produce a consensus research plan giving the campaign's goals and defining its program. The pre-campaign workshops will be open to all interested participants. The consensus research plan will form the basis of an NSF announcement of opportunity to participate in the campaign.

Initial Phase

1. Workshop to determine consensus research plan
2. Announcement of campaign opportunity
3. Proposal preparation and submission
4. Regular peer review
5. Review by specialist panel appointed for the campaign
6. Selection by NSF program director of proposals to be funded

Operational Phase

During this phase the groups selected would carry out the research and attend yearly workshops organized by the campaign coordinator. At these meetings, which should include campaign participants as well as other interested individuals, an interchange of ideas and results would take place along with an assessment of obstacles to progress and how to overcome them.

Assessment Phase

This phase at the end of the three-year TC period would involve a workshop open to all scientists and attended by the campaign review panel. During this workshop the review panel would assess the progress made and decide whether or to what extent the TC should be continued. Worthwhile projects might also be supported in the regular NSF mode after the termination of the TC. Normally a decrease in campaign funding to a substantially lower level—in some cases zero—would occur at this point. But one could also visualize situations in which it would be advisable for the campaign to be continued for another period at the same level or even at an expanded level of funding.

It is important that the implementation of each TC be carried out in a flexible manner. For example, if one group has made a significant advance that could benefit another campaign project, it would be highly desirable either to redirect the subsequent work in response to the new development, or perhaps to combine the groups so as to take advantage of the advance. On the other hand, if a group were not making progress on a particular project, it might be wise to cancel that effort and use the resources elsewhere. For this reason we suggest that there be frequent reviews of progress and communication of results. We suggest that regular workshops be held for the purposes of reviewing and communicating the results of the campaign projects. Even more frequent updates of progress could be made by having monthly reports by each group made available, for example, through the SPAN network.

There is an important caveat to all the above. In proposing the use of a theory campaign format we do not imply that most of the fundamental theoretical problems underlying

magnetospheric and ionospheric physics could be solved nor, in the long run, optimally dealt with in this mode. It is presumed that the traditional research grant funding system will continue undisturbed by the existence of a campaign effort except for benefiting from the campaign results. Indeed, ongoing investigations by individual P.I.'s should continue to represent the baseline for NSF-funded geospace research; such research programs will always provide the necessary stimulation, stability and continuity of the overall research initiative. We do argue, however, that an effective way to use incremental funding and speed up progress on certain specific large-scale problems in STR is to place the TC's at the focus of an intensive short-term effort by several different multidisciplinary research groups.

2.2 Strategy for Determining Specific Theory Campaign Projects

The strategy for selecting TC projects rests basically on two criteria; 1) Each campaign project should address an important physical problem whose solution will facilitate the development of a Geospace Environment Model; 2) Each campaign project should be coordinated with pertinent data sets, particularly ground-based observations such as ionospheric signatures of magnetospheric processes, but also with existing reduced data from spacecraft. These two criteria do not necessarily have to be met for each campaign project to be selected, but it is urged that these criteria be given significant weight in the selection process.

The first criterion is meant to ensure that the campaign will further the over-all goal of developing a predictive global geospace environment model. For example, MHD modeling of the entire magnetosphere is hampered by our incomplete understanding of physical processes at the magnetopause, and also by the breakdown of the applicability of MHD at the magnetopause. A focused theoretical initiative on the magnetopause could lead to a new way of treating the magnetopause in the global modeling effort.

The second criterion is meant to ensure that the theoretical efforts confront and make use of observations. We strongly recommend that each campaign project have a theorist as principal investigator, but that one or more experimentalists participate as co-investigators. The project proposal should describe how the observational data will be used in the formulation, resolution, or testing of the proposed theoretical initiative. We also urge that these campaign projects, where appropriate and feasible, be closely coordinated with new observational initiatives.

2.3 The Projects and Their Priorities

The following campaign projects constitute a sequence of initiatives designed to lead progressively to a comprehensive Geospace Environment Model. Each category represents a problem so large that it transcends the capabilities of any individual research group and thus would require a coordinated effort by several such groups. In some instances

it is not clear at the outset which of two or more approaches would lead to the most efficient solution of the problem; for such instances the TC format would provide a framework for finding the best approach.

The following campaigns have been placed in an ordered sequence. In most cases this ordering has been in recognition of the necessity of making substantial progress in one area to provide information to facilitate research on a later task. Ordering is also partially determined by the coordinated ground-based and balloon observation campaigns to be carried out (Chapter III), and with cognizance of ongoing and planned space-flight opportunities where newly reduced data and their interpretation are expected to contribute significantly to theoretical and modeling efforts.

The suggested campaigns should be reviewed periodically, as discussed earlier. No committee has the ability to predict future developments well enough to recommend the research to be conducted more than a few years in advance. This is particularly so in such a rapidly evolving field as solar-terrestrial science.

2.3.1 Magnetopause and Boundary Layer Physics

As a result of large magnetic Reynolds numbers and, therefore, of nearly frozen-in magnetic fields, the solar wind plasma impinging on the earth's magnetic field does not readily leave solar-wind field lines and move onto terrestrial ones. Instead, the plasma flows around the geomagnetic field compressing and deforming it into the magnetospheric cavity. The boundary of this cavity is an electric current sheet called the magnetopause. While transport of mass, momentum, energy and magnetic flux across this layer is strongly impeded, it is nevertheless this transport that drives much of the general internal plasma circulation and other dynamic phenomena inside the magnetosphere. For this reason, a detailed quantitative model of transport across the magnetopause is an indispensable building block in the construction of a general magnetospheric circulation model.

Attaining a detailed understanding of transport processes operative at the magnetopause has proved to be a difficult task. From a variety of observational studies and theoretical considerations it has emerged that the principal portion of this transport occurs via the process of magnetic field reconnection. But other processes, such as direct entry into the cusp regions or diffusive entry over large portions of the magnetopause via microscopic or macroscopic (Kelvin-Helmholtz) plasma turbulence, may also play a nonnegligible role.

In spite of extensive but largely uncoordinated research efforts in the past, the reconnection process itself remains enigmatic. It appears to be controlled not only by the southward component of the solar-wind magnetic field but also by other global boundary conditions as well as by local microscopic plasma processes at the reconnection site. From in-situ observations it appears that, depending on

such factors, the process may occur either in a quasisteady form (quasisteady reconnection, or QSR) or in a time-dependent “patchy” or multiple form which manifests itself in specific signatures of the magnetic field and other quantities measured at the magnetopause, called flux transfer events (FTEs).

Although two-dimensional computer simulations have verified the occurrence of steady, pulsating and multiple versions of reconnection, we have no firm knowledge of the three-dimensional aspects of QSR or FTEs, nor of the parameters that determine the occurrence of one form of the process or the other. And we do not know what is the spatial distribution of reconnection or even the principal locations of the single or multiple reconnection sites on the magnetopause surface. The total amount of reconnected magnetic flux can be inferred from measurements of the polar-cap potential, but at present we do not have a clear theoretical understanding of the parameters that influence this total amount.

Further detailed information concerning the reconnection process in its magnetopause setting is undoubtedly obtainable from existing in-situ data sets from spacecraft such as ISEE 1 and 2 or AMPTE, and much more will come from the Cluster mission. However, because of the local nature of such measurements, it will remain a difficult task to construct a comprehensive global picture of the reconnection geometry from these sources. In principle, one could also monitor the reconnection process via the plasma properties and motions, and through the currents into and out of the dayside auroral and polar ionosphere, thereby obtaining a more global view and a better description of the process in its various forms. The observational part of this effort comprises Project GAMBLE, described in the next chapter.

In order to succeed in these efforts, one must first learn how to interpret the ionospheric signatures such as FTE footprints in terms of corresponding geometries and locations at the magnetopause. To achieve this goal it will be necessary to develop analytical and computer simulation models of three-dimensional time-dependent reconnection in the presence of partial line-tying to the ionosphere; a detailed quantitative mapping into the ionosphere along magnetic field lines adjacent to the magnetopause will also be needed. For the latter purpose, a magnetospheric B-field model, valid out to the magnetopause, will be indispensable. Further, it will be necessary to develop quantitative dynamical models of the boundary layer regions inside the magnetopause that are occupied by a streaming plasma of solar-wind origin, and of the self-consistent coupling of these layers via field-aligned currents to the ionosphere. In this coupling, field-aligned potential differences are expected to occur that produce particle precipitation into the ionosphere and introduce effects such as low-pass filtering in the ionospheric imaging of spatial structures located in the magnetopause and boundary layer.

In summary, it is proposed that all available tools—

theoretical analysis and modeling, computer simulation, and analysis of ground-based, ionospheric as well as in situ data—be marshaled in a concerted effort to produce quantitative information about the important transport processes at the magnetopause.

2.3.2 Model of the Magnetosheath

An accurate user-friendly numerical model of the magnetosheath to project the solar wind parameters from the bow-shock to the magnetopause is needed for studies of magnetopause transfer processes, for interpretation of data obtained in the Cluster mission, and as a component of the Geospace Environmental Model. It should operate on a sufficiently fine grid to generate accurate solutions of the ideal-MHD equations, with particular emphasis on the calculation of the magnetic field, velocity, pressure, and density just outside the magnetopause. The model should be demonstrably accurate for the case where the magnetopause is an ideal tangential discontinuity. Moreover, the magnetopause should be treated as a free boundary whose position might, for example, be governed by the condition that the magnetosheath pressure balances the total pressure inside; the condition's variable—pressure in this case—would be a user-specified function. A necessary part of code-testing would be an extensive comparison with magnetosheath observations.

The magnetosheath code would have enhanced scientific value if it were flexible enough to represent time-dependence and/or nonzero B_{normal} . A full time-dependent model could be used to study the dynamical changes in the magnetosheath that accompany a change in interplanetary magnetic field. A magnetosheath code with nonzero B_{normal} might be used interactively with models of magnetospheric transfer processes.

The magnetosheath model would be straightforward to develop. As results from it would be useful as input for the magnetopause transfer process and B-field modeling projects, this model would be an appropriate first project. A Theory Campaign aimed at the development of an accurate MHD model of the magnetosheath has a high probability of success, given the current level of sophistication of the leading MHD modeling groups. This MHD model development is an initial, global approach which aims at approximating the system. It is expected that at some later point a kinetic model would be developed to provide a more specific and detailed picture of the magnetosheath.

2.3.3 Global Modeling of the Magnetospheric B-Field

The most essential tool for organizing and analyzing magnetospheric data, for constructing successful magnetospheric theories, and for tracing the relationship between theory and observation is a model of the magnetospheric B-field that is accurate, reliable, adaptable, and easy to generate. Various field models already exist, of course, but no model so far developed has been found to meet all the needs of the research community. The validity of most models is limited to geocentric distances of less than about $8 R_E$ (earth radii). Such a limitation precludes the mapping of magnetic-field lines, charged-particle populations, and

electrostatic potentials between the ionosphere and the magnetospheric boundary layers (magnetopause and plasma sheet) or the magnetotail. It also precludes accurate mapping of field lines between conjugate regions of the north and south high-latitude ionospheres. Other models are global in principle but fail to include Birkeland currents and ring currents, for example. Some otherwise successful models prescribe a sharp inner boundary for the cross-tail current distribution, while others (by prescribing a flat current sheet) are limited in applicability to the untilted-dipole case (dipole moment perpendicular to solar-wind velocity). Still other models are qualitatively reasonable in many respects but fail to reproduce quantitatively the observed B-field.

An accurate magnetic field model for the distant magnetosphere, in particular the plasma sheet and the transition region to the ring current, is of vital importance for calculating the orbits of energetic particles generated during a substorm. Many previous models include artificially strong field gradients in transition regions that introduce large and unrealistic perturbations of the calculated orbits. Thus it is impossible to use such calculations for determining the position of the source for these particles.

The lack of a good magnetic field model has also prevented the solution of such fundamental problems as the mapping of region 1 and region 2 Birkeland currents into the magnetotail. For instance, we do not really know whether the auroral arc currents map into the plasma sheet boundary layer, the inner edge of the central plasma sheet, or somewhere in between. The problem is compounded by the fact that one must include currents in the distant magnetosphere. It is often assumed that the plasma sheet boundary layer maps along the magnetic field, i.e., that there is no component of the magnetic field normal to it. This is by no means obvious, but no magnetic field model at the present time would allow one to determine this.

A major goal of this TC program would be the development of an accurate, reliable, and adaptable global model for the magnetospheric B-field. It should be user-friendly and easy to generate. Moreover, the model should include the consequences of all major current systems. Above all, it should accurately reproduce the magnetic field actually observed in space for different states of magnetic activity upon proper selection of the adjustable parameters of the model.

The development of a reliable magnetic field model does not mean just the fitting of an assumed functional form to measurements along a spacecraft trajectory. This method is successfully used for modeling the curl-free magnetic fields in the inner regions of planetary magnetospheres where local current densities are zero or very small. In the outer regions of the magnetosphere, however, the magnetic field is strongly influenced by local currents and hence plasma pressure gradients and flows. Magnetic field models must thus be guided by theoretical considerations such as pressure balance. Significant progress has been made in deriving models based on isotropic pressure and zero flow. But we know that flows and pressure anisotropies do occur in the magnetotail. The inclusion of these effects into the theoretical models would be a major task for this TC. In addition, theoretical models are often based on analytically

simple forms of the spatial pressure variation which do not accurately represent the data. It will be essential to numerically solve the MHD equations for more complex but realistic pressure distributions. The treatment of the magnetopause boundary condition (e.g., the magnetotail flaring angle) needs to be improved. Finally, it is imperative to address the question of time-dependent magnetic field models, including induced electric fields. These tasks require both analytic, numerical and data analysis work which can probably not all be handled adequately by one group. It is very important that the various groups participating in this TC work very closely with each other in an interactive mode, exchanging models, data and numerical codes for testing the consistency of the models.

2.3.4 Magnetotail and Substorms

The magnetotail constitutes a crucial channel for the flow of energy from the solar wind to the ionosphere and atmosphere. According to current theories, solar wind flow energy drives reconnection on the dayside magnetopause, connecting the terrestrial and solar wind magnetic fields. Field lines are swept back to the magnetotail, where magnetic energy is built up. This stored energy may be converted to plasma kinetic energy in one of two ways: continuously or impulsively. In either case, this kinetic energy appears in the energization of electrons and ions which stream along the magnetic field in the plasma sheet boundary layer toward the earth, eventually resulting in energy deposition in the high latitude ionosphere and upper atmosphere. This deposition manifests itself in many ways, including aurora, ionospheric currents and electric fields, and atmospheric heating, all of which can be monitored by ground-based observations. In addition, rapid heating of the central plasma sheet ions and electrons occurs during the expansion phase of a substorm. These particles drift towards the earth and can be trapped into stable drift orbits, populating the ring current and radiation belt. The very rapid increase of energetic particle fluxes at synchronous orbit (injection) is presumably a consequence of this heating and subsequent earthward convection.

Our understanding of the tail and its dynamic changes during substorms is fairly sophisticated. The theory of reconnection in the plasma sheet is well developed. Three-dimensional numerical simulations have been made, clarifying the relation between convective $\mathbf{E} \times \mathbf{B}$ flow and streaming along field lines. However, the simulations usually include unrealistically large resistivities (numerical or phenomenological). A major task of this TC would be the development of more realistic three-dimensional codes to model reconnection in the tail. Such efforts will be based on the three-dimensional magnetic field models developed in the B-field modeling TC.

Since Coulomb collisions do not provide enough resistivity, it has often been assumed that wave-particle interactions play a major role in the reconnection process. The nature of the wave involved is, however, poorly known. The theory of waves in the tail is complicated because of strong north-south gradients in the plasma sheet and its boundary layer—yet most theories treat homogeneous media. The theory and simulation of waves in inhomogeneous media is thus of

crucial importance and will be a major task of this TC. For example, the three MHD modes are strongly coupled by the inhomogeneities. Compressive waves in the lobe can resonantly mode-convert to shear Alfvén waves in the plasma sheet boundary layer (PSBL), which in turn can be damped by finite gyroradius and/or electron inertia effects. It has been suggested recently that this resonant mode conversion and damping are a major source of heating for the plasma sheet and the generation of small scale multiple field-aligned current sheets in the plasma sheet boundary layer, which may be the source of multiple auroral arcs.

Some features in the energetic particle distribution functions observed in the PSBL, such as bidirectional streaming, cannot be explained in the MHD framework. The study of single particle trajectories has proven to be a fruitful approach. These studies are, however, limited by rather simple magnetic field models of the tail. Once better field models are available, these calculations should be repeated. It has been suggested that the chaotic nature of the particle orbits near the neutral line and the current sheet in the plasma sheet may play the role of a resistivity and thus be of major importance for the theory of reconnection.

In the distant tail one often observes tailward-moving closed field line structures together with tailward moving plasma, the so-called plasmoids, which are believed to be a result of reconnection in the near-earth plasma sheet. The three-dimensional structure of these plasmoids is not well understood. The acceleration of plasmoids to the observed speeds of several 100 km/s is also an important phenomenon which should be addressed in this TC.

Most theories of substorms have dealt with the growth and expansion phase. No comparably sophisticated models are available for the recovery phase. The development of a theory for the recovery phase should thus be a major goal of this TC.

We anticipate that significant progress will be made before the start of this TC and that new questions will have arisen. Thus the previous description of the outstanding scientific questions should be viewed as a guide rather than as a complete list.

2.3.5 Convection and Coupling

The interaction of the solar wind with the magnetosphere drives the global convection of the magnetosphere, which maps into the ionosphere in the polar cap and the auroral zone. While ground-based instruments can determine the convection pattern in the ionosphere, mapping this pattern into the outer magnetosphere requires a knowledge not only of the global structure of the magnetic field but also of plasma processes which may decouple magnetospheric and ionospheric convection patterns. The flow of plasma in the collisionless magnetosphere is dominated by the $\mathbf{E} \times \mathbf{B}$ drift; therefore, plasma convection cannot be divorced from the electrodynamics of the magnetosphere. The electric field in the collisional ionosphere drives currents which must close by field-aligned currents connecting the ionosphere to the boundary layer regions. If these field-aligned currents are intense enough, current-driven plasma instabilities can generate parallel potential drops. These parallel electric fields cause the convection electric field in the magnetosphere and

ionosphere to be decoupled, i.e., not related to each other by a simple mapping relationship.

A campaign focused on the coupling of the magnetospheric convection to the ionosphere would include a study of the generation and propagation of field-aligned currents and parallel electric fields, the influence of the ionospheric conductivity pattern on convection, and the relation of the boundary layer flow to the ionospheric conditions. Many of these subjects have been discussed in and of themselves; e.g., various microscopic plasma simulations of the formation of parallel electric fields due to double layers have been performed. An enhanced and coordinated effort must be made, however, to place these microscopic processes in the context of a mesoscale framework which considers the evolution of an entire flux tube.

Such a framework would consider the interactions of these small scale processes. For example, the current-generation region is coupled in a time-dependent fashion to the parallel electric field region by means of Alfvén waves. Particles energized in parallel electric field regions can propagate to and have effects on other regions of the magnetosphere. Ionospheric ions are accelerated upward and mass-load the outer magnetosphere, producing effects which have yet to be fully explored and understood. Electrons accelerated downward impact the atmosphere, producing additional ionization which modifies the ionospheric conductivity. Such localized conductivity enhancements modify both the convection pattern and the current pattern by radiating Alfvén waves back into the magnetosphere. These small scale interactions may become unstable and grow in amplitude to the point where they may have macroscopic consequences.

This TC would interact with others that focus on the boundary layer and magnetopause, and would use results from magnetic field modeling to map the convection between the magnetosphere and ionosphere. It could enable ground-based measurements of ionospheric convection to be used as a probe of the general circulation of the magnetosphere as well as establishing models for the ground signature of smaller scale phenomena such as flux transfer events. The coupling processes studied in this program would be essential ingredients in the ultimate establishment of a general circulation model of magnetospheric convection.

2.3.6 Global Plasma Model

The purpose of this campaign is to develop a global plasma model of the terrestrial magnetosphere that includes sources, energization, transport, and sinks of charged particles at all energies between the base of the ionosphere to the outer boundary of the magnetosphere. The approach will involve the generation of both empirical and theoretical models to quantify the phase space distribution function for the important compositional and charge state species in the magnetospheric system. The ultimate goal of the model would be to predict the magnetospheric plasma configuration for given changes in the input functions such as source strength, transport characteristics, and available free energy in the system, and to define the feedback processes associated with source strength, transport, and energization that

result from reconfiguration of the plasma. These plasma feedback processes are extremely important in the study of impulsive phenomena such as magnetic substorms.

The two principal components of this campaign are the generation of a global empirical model and the utilization of the model in the theoretical study of plasma source strength, energization and transport. The following description of the global plasma modeling campaign first addresses the generation of an empirical model and then discusses the theoretical studies necessary to understand the evolution of plasma in the magnetospheric system.

Empirical Model: An important approach to a global plasma model is the development of an empirical model which draws together spacecraft and ground-based observations in a statistically coherent form. Such a model serves a two-fold purpose. It provides realistic input for theoretical studies of physical processes that require a knowledge of the plasma environment. This would include global-scale studies for which total global information could never be procured from simultaneous observations. It would also serve as a guide and a means for testing theoretical models that embody relevant physics and attempt to predict the response of the plasma environment to one or more variable influences. As our understanding becomes more comprehensive, the empirical model can be improved by using the simulation results to obtain a more appropriate form for representing the data empirically.

Theoretical Studies: A stumbling block in the development of a global plasma model is our incomplete understanding of the effects of energization during transport, combined with the additional complication of having two sources of plasma in the magnetosphere (the solar wind and the ionosphere). Furthermore, the particle populations that occupy any particular location at any one time may contain components that are closely related to their source as well as components that have been extensively processed in the magnetosphere and thus bear little resemblance to their respective source populations.

Theoretical efforts will be required to show how plasma energization moves plasma from one energy domain to another. Cold plasma entering the system at the base of the ionosphere experiences heating and/or acceleration in some cases, and in other situations expands into the magnetosphere without substantial heating. Solar wind plasma enters across the magnetopause in the dayside cusps and through the tail and experiences energy redistribution in the entry process. A theoretical treatment of wave heating and electric field acceleration guided by observations must be incorporated into the model in a self-consistent fashion. This is necessary to evaluate the effect of the generation of additional plasma waves and changes in the electric field that result from plasma reconfiguration. The development of empirical models of the multi-ion plasmas, which are known to be present throughout the magnetosphere, is a necessary step leading to a realistic theoretical treatment of particle redistribution and acceleration processes. Theoretical studies of processes such as charge exchange, plasma wave generation and propagation, and various wave-particle interactions are profoundly affected by the presence of more than one ion species. The wave dispersion relations develop

new roots, new wave mode solutions appear, and growth rates are modified when more than a single ion species is considered. Owing to the fact that many fundamental plasma-physical interactions take on a completely different character in the presence of multi-ion plasmas, many theoretical studies of particle stability in the magnetosphere need an accurate empirical plasma model that includes composition.

The development of a global plasma model will draw together the empirical models and the theoretical studies into a comprehensive description of the magnetospheric plasma. As noted, this TC will require a merging of ground-based and *in situ* particle observations, numerical modeling, and analytical investigation.

2.3.7 Development of General Circulation Models for the Magnetosphere

With the completion of theoretical campaigns 1-6 described above and the analysis of data from the ground- and space-based observational programs planned for the early and mid 1990's, development of realistic comprehensive large-scale theoretical models of the magnetosphere should be feasible. These "magnetospheric general circulation models" (MGCMs) would be conceptually analogous to the general circulation models that have been used extensively for studies of tropospheric weather.

An MGCM would have to take into account the major physical insights resulting from the Theory Campaigns on magnetosphere transfer processes, the magnetotail, the global magnetic field, and plasma circulation, as well as the work on coupling. It would also have to include the physics of the inner plasma sheet and ring-current regions, as studied and checked with observations tested in years of work with inner-magnetospheric convection models. Further, it should be capable of coupling with realistic numerical models of the ionosphere and thermosphere.

Beyond the requirement of making use of our best physical understanding of the crucial magnetospheric processes, the only criterion for ultimate success in this modeling effort will lie in the model's ability to make accurate predictions of a wide variety of magnetospheric phenomena. Particularly crucial will be its ability to predict polar-cap flow patterns for various orientations of the IMF, as established by the greatly expanded ground-based observations discussed in the next chapter.

It is too early to specify what computational form such a magnetospheric general circulation model should take. One possibility would be a highly developed 3-D global MHD model, with transport coefficients carefully adjusted for realistic representation of the essential physics of magnetopause transfer processes, magnetotail reconnection, and substorms, field-aligned potential drops, ring-current dynamics, etc. Alternatively, an MGCM might consist of a series of models based on different approximations as appropriate for different regions, but hooked together self-consistently at appropriately defined free boundaries. Treatment of certain problems, such as particle acceleration, will probably require the use of auxiliary codes that follow individual particles in the electric and magnetic field computed using an MHD or other fluid-type approach. Uti-

lization of such procedures might greatly increase the capability of a MGCM to provide insights into the magnetosphere's rich variety of plasma phenomena.

The development of magnetospheric general circulation models, embodying our most advanced understanding of the physical processes that affect the large-scale dynamics of the system, will constitute a major milestone in the advancement of solar-terrestrial science.

2.4 Budget

It is obvious from the preceding discussion that different TCs are interdependent and should, ideally, be carried out nearly simultaneously. Neither the limited manpower of the discipline nor the financial resources of NSF would allow this to be a practical course of action. Instead, the TCs should be phased according to a well-established plan. The first TC on Magnetopause and Boundary Layer Physics should start in 1990. One year later the TCs on Magnetosheath and Global Modeling of the Magnetospheric B-field would start; the Magnetotail and Substorm TC should begin in the third year. In the fourth year the first TC would be completed and the fifth TC on Convection and Coupling would begin. In the following year the Global Plasma Model TC would start; the magnetosheath and magnetic field modeling TCs would be completed; etc. (see **Table 2** on page 8.)

GEM also involves observational campaigns which must be closely coordinated with TCs. The observational campaign on cusp signatures, for example, is related to the first TC and should thus run concurrently with it as shown in **Table 2**. The observation of global features of substorms should run parallel to the fourth TC, etc.

TABLE 3a
PROTOTYPE BUDGET FOR A THEORY CAMPAIGN

| | | |
|----------|--------------------|-----------------------|
| 1st year | | |
| | Research groups | 650,000 |
| | 1st year workshop | 50,000 |
| | | <hr/> 700,000 |
| 2nd year | | |
| | Research groups | 910,000 |
| | 2nd year workshops | 90,000 |
| | | <hr/> 1,000,000 |
| 3rd year | | |
| | Research groups | 920,000 |
| | 3rd year workshop | 80,000 |
| | | <hr/> 1,000,000 |
| | Total | <hr/> <hr/> 2,700,000 |

Obviously, the level of funding required for different TCs need not be the same and should remain flexible. It is premature to plan detailed budgets for each particular campaign at this time. The proposed budget for a typical three-year theory campaign, is shown on **Table 3a**; the total budget outline is given in **Table 3b**.

TABLE 3b
THEORY BUDGET OUTLINE
(IN K\$)

| | '91 | '92 | '93 | '94 | '95 | '96 |
|---------------------------|------------|-------------|-------------|-------------|-------------|-------------|
| Magnetopause and Boundary | 700 | 1000 | 1000 | | | |
| Magnetosheath | | 500 | 500 | 500 | | |
| B-Field | | 250 | 500 | 500 | 250 | |
| Tail and Substorms | | | 700 | 1000 | 1000 | |
| Convection and Coupling | | | | 500 | 800 | 800 |
| Global Plasma Model | | | | | 1000 | 1000 |
| GCM | | | | | | 1000 |
| TOTAL | 700 | 1750 | 2700 | 2500 | 3050 | 2800 |

The campaign coordinator appointed by the agency will oversee and facilitate the interaction and cooperation among the research groups and NSF. He/she will also be responsible for the coordination of the data sets relevant to the TC. It is conceivable that he/she will be in charge of the relevant Discipline Data Center described in Chapter IV. The coordinator will also organize the TC workshops discussed above. It is expected that the results of each TC will be published either in a special issue of the Journal of Geophysical Research or an AGU monograph. The campaign coordinator will be responsible for the production of this final TC report. He/she will also be an advisor to the evaluation committee.

The funding for each group of investigators should be generous enough to allow groups to concentrate a significant fraction of their manpower on the project. It is very likely that during a TC some groups may choose to work exclusively on the TC project. In that case their normal individual funding may be reduced. This would free additional resources that NSF can spend on GEM, for instance, to support the participation of young researchers.

CHAPTER III:

Observations and Measurements

3.1 Introduction

The implementation of the scientific goal of GEM requires the coordination of the theory campaigns discussed in Chapter II with new multi-point measurement campaigns. The ultimate observational goal of GEM is the production of high-resolution “maps” of the global phenomena which control the magnetospheric dynamics on a continuous but highly variable basis. Such maps are difficult if not impossible to obtain from spacecraft measurements alone, even if multi-spacecraft programs are involved. Chains and clusters of new and improved ground-based and airborne detectors are needed. The GEM program provides the scientific and logistic framework for the coordination of diverse observations in such a way that they can be directly linked to the various Theory Campaigns (see **Table 2**). In this section we describe observational projects which will be correlated with the TCs discussed in Chapter II.

In several aspects the observational program of GEM will be different from past programs:

1. Since the observational projects (with one exception) will be conducted in parallel with Theoretical Campaign counterparts, experimentalists will be able to help theorists to develop and test models, while theorists will guide experimenters to look for theoretically predicted phenomena.
2. A specific distribution of new instruments with state-of-the-art technology will be proposed, often as a complement to existing observatories, to answer specific questions. Taking into account recent advances in theoretical and observational studies, emphasis will be given to the task of inferring three-dimensional magnetospheric processes from multi-point ground-based observations.
3. The new instruments will be streamlined for fast and sophisticated data-processing and data exchange among the participants. The acquisition of state-of-the-art processors will be an important part of the observational program.
4. Specific efforts will be made by the observational program to obtain the multi-point, long-time data base required to study the global electrodynamic coupling between the ionosphere, mesosphere and the troposphere.

Although the GEM observational program will not be tied to any specific satellite project, it will be coordinated with space missions, such as the NASA-ESA-ISAS International Solar Terrestrial Physics program (ISTP), CLUSTER and others.

3.2 Proposed Observational Initiatives

Two comprehensive research thrusts are proposed, each one consisting of several ground-based and balloon-borne measurement programs.

The theoretical/modeling requirements outlined in Chapter II will define the observational initiatives of the first thrust and point the way toward formulating plans for their implementation. It will focus on the study of ionospheric manifestations of energy transfer processes from the solar wind to the magnetosphere and their projection onto the ionosphere, emphasizing phenomena associated with the dayside cusp, the polar cap, and the auroral region on the nightside.

The second research thrust will focus on global electrodynamic interactions of the magnetosphere and the atmosphere, concentrating on vertical coupling in the altitude range between about 40 and about 100 km.

The scientific rationale for the focus of each research thrust is presented below. Research plans describing specific Observing Campaigns in more detail, including considerations of instrumentation and siting, are given in section 3.4. Estimates of the cost and the time scale for implementing various phases of the programs are presented in section 3.5.

3.2.1 Energy Transfer from the Solar Wind to the Magnetosphere

Observations will be obtained in the following regions : (i) The dayside cusp, mainly to study small- and large-scale effects of plasma transport and magnetic reconnection at the dayside magnetopause (regions I and II in **Figure 2**); (ii) The subauroral latitudes on the nightside, to study the gross features of ionospheric and field-aligned currents and provide essential information on the timing and location of magnetospheric substorms (region IV in **Figure 2**); and (iii) The polar cap, to study the global magnetospheric convection in the outer magnetosphere and open field line region (region III in **Figure 2**).

(i) Dayside cusp

Recent satellite observations of the interaction between the solar wind and the magnetosphere have revealed the great temporal and spatial complexity in this interaction and have led to major progress in the theory. However, in order to fully understand the microscopic processes associated with the transport of mass, momentum, energy and magnetic flux across the magnetopause and the global architecture of this transfer, it will be necessary to observe the interaction with higher resolution in time and space. Even though space missions such as CLUSTER will enhance our capabilities significantly, in situ satellite measurements are inherently limited and need to be complemented by ground-based observations. For these reasons, measurements in the ionospheric cusp and other auroral regions of processes linked directly to the outer magnetospheric boundary regions are of central importance for determining the dynamics of magnetospheric boundary layers.

For instance, Flux Transfer Events (FTEs) and other

processes associated with the boundary may be linked to signatures observable on the equatorward side of the magnetopause projection onto the ionosphere. The search for specific ionospheric signatures of such boundary processes in the optical aurora, energetic particle precipitation, the ionospheric electric field, horizontal and field-aligned current flows, and ULF magnetic variations is currently an area of intense investigation. Recent observations with both ground-based and balloon-borne instruments indeed suggest that such signatures may be present.

(ii) Subauroral latitudes on the nightside

The role of the magnetotail and the ionosphere in the development, onset, growth and decay of magnetospheric substorms remains a subject of intense debate. Ionospheric manifestations of substorm dynamics are amenable to study by ground-based and airborne measurements (indeed, such measurements offer some distinct advantages of temporal continuity with respect to satellites). Instruments placed at very high latitudes in order to carry out investigations under (i) would also provide measurements essential for the study of some aspects of the magnetotail-substorm problem. However, it is important that these be augmented with networks of subauroral ground magnetometers capable of delineating the macroscopic configuration of the intense field-aligned and horizontal current flows associated with substorm effects on the nightside. In particular, the east-west component variations of the magnetic field in the subauroral zone can provide crucial information on the distribution of the field-aligned currents which flow in and out from the ionosphere.

(iii) Polar cap

An important problem in magnetospheric and ionospheric physics concerns the global convection pattern in the polar regions, and its time-dependence. At present, average patterns can be obtained from satellite, balloon or incoherent scatter radar measurements; during the course of one day, individual ground-based instruments can measure the convection over a limited latitudinal range. However, it is not possible to determine global and/or instantaneous patterns with such techniques.

Several studies using balloons and radars have successfully obtained “snapshots” of the global convection pattern during limited time intervals (less or equal 3 to 5 days), with relatively high time-resolution (e.g., 15 minute averages) but low spatial resolution (6 to 10 globally spaced measurements). While these earlier studies have produced some significant results, perhaps the most important conclusion from them is that very little is known about the instantaneous global convection over the entire polar cap and the auroral oval. It is necessary to obtain **both** high resolution (in space and time) as well as global coverage to solve energy transfer and electrodynamic coupling problems. At present, however, the sparsity of instruments to measure on a global scale plasma drifts prevents us from obtaining the instantaneous convection pattern within the polar cap and the auroral oval with sufficient accuracy.

The electric potential drop across the polar cap is another important parameter relevant to solar wind-magnetosphere interaction, because it provides information on the total

electromotive energy of the system. At the present time, this parameter is available by a “remote sensing” technique with ground-level magnetometers and a specially designed computer code. However, there is still much uncertainty in this method because of the lack of adequate global ionospheric conductivity models. Polar-orbiting satellites can provide a value of this parameter only every 100 minutes. Yet reliable estimates of the cross-polar-cap potential must be available continuously and with good temporal resolution for periods of many days, in order to understand how the solar-terrestrial system responds to changes in the input conditions from the solar wind.

3.2.2 Vertical Coupling in the Middle Atmosphere

The solar-terrestrial system has its lower boundary in the middle atmosphere (region VI in **Figure 2**), the region lying between roughly 15 km and 100 km above the earth’s surface. The middle atmosphere contains within it both the lower reaches of the ionosphere (the D-region), and the stratospheric ozone layer, whose properties have been a matter of major concern in recent years because of its importance to the biosphere and its vulnerability to anthropogenic chemical destruction.

While much has been learned about the dynamics and neutral chemistry of the middle atmosphere as a result of this concern, and from such international programs as the Middle Atmosphere Program (MAP), our knowledge of the electrodynamic properties of the middle atmosphere remains woefully inadequate. These electrodynamic properties are of central importance to the problem of coupling between the magnetosphere and the atmosphere, and perhaps also to the more remote problem of coupling between the solar wind and the magnetosphere, since the flow of current that this coupling involves must necessarily depend on the resistive loading provided by the lower ionosphere.

The electrodynamic parameter of primary importance in this connection is the conductivity. The conductivity is a function of the concentrations of free electrons and both positive and negative ions, as well as the mass and mobility of the ion species. While we have a basic understanding of the processes that determine these parameters, the observational data base is exceedingly sparse, and is not yet adequate for testing the predictions of the rather simple models of middle-atmosphere electrical properties that have been constructed.

A new source of ionization for the middle atmosphere has recently been reported in the form of intense fluxes of highly relativistic electrons precipitating from the outer radiation belt. These electrons have sufficient energy to reach the upper stratosphere, and their bremsstrahlung X-rays will penetrate still further into the atmosphere. They occur in events of relatively short duration, and their occurrence frequency does not show a direct relationship to the solar cycle. While monitoring of these electrons will be performed by direct spacecraft techniques, their significance as a source of D-region ionization and their impact on the neutral chemistry of the middle atmosphere are not well known.

The middle atmosphere region is particularly important

because the downward coupling of auroral energy cannot be understood without knowing how the middle atmosphere responds to the thermosphere above. Similarly, effects of tropospheric processes on the thermosphere and ionosphere cannot be understood without knowing how the middle atmosphere responds to the troposphere and stratosphere below. Lightning from below and energetic electrons from above (which can penetrate deep into this region) appear to play major roles in the two-way coupling processes. Their effects, though perhaps subtle, may lead to important interactions between the magnetosphere and the atmosphere (see **Figure 4** on page 2.)

Ground-based investigations of middle atmosphere phenomena will fall largely under the aegis of the CEDAR program. However, some topics concerned with magnetosphere-atmosphere coupling, but not emphasized in the CEDAR program (e.g., the effects of lightning and relativistic electron precipitation, and the study of the electro-dynamics of the middle atmosphere with stratospheric long-duration balloon payloads) are important in the context of global environment modeling and thus are properly a focus of the GEM initiative.

3.3 Instrumentation

The magnetosphere-ionosphere-neutral atmosphere system is never found in a steady state. Ground-based and balloon-borne measurements are essential to understand how the system reacts to the continuously changing input from the solar wind, provided the appropriate instrumentation is properly located. A comprehensive GEM program will include the instrumentation listed on **Table 4**. This table also lists the effect measured by each type of instrument as well as the principal cause for the effect.

It should be emphasized that, quite generally, in the development of new instruments, data recording systems should be streamlined for fast data processing and data exchange among the participants of an Observing Campaign. Relevant data also should be available to the associated Theoretical Campaigns and modeling efforts. Acquisition of state-of-the-art data processors is thus an essential part of the GEM observational program.

By definition, the experimental part of the GEM program would have a strong international component, since several projects will require data from instruments deployed in

TABLE 4
PROTOTYPE INSTRUMENTATION FOR THE STUDY OF GIVEN PROCESSES

| <u>Cause</u> | <u>Effect</u> | <u>Instrument</u> |
|--|---|---|
| Particle Precipitation | Aurora | Optical Imagers, Incoherent Scatter Radars, Photometers, Optical Detectors (balloons) |
| | Cosmic Noise Absorption | Riometers |
| | Auroral X-rays | X-ray Detector, Imager (balloons) |
| Ionospheric Currents | Geomagnetic Variations | Magnetometers, Incoherent Scatter Radars |
| | Convection | Ion Drifts Electron Drifts Electric Potential |
| MHD waves | ULF Magnetic Pulsations | Induction Magnetometers Incoherent Scatter Radars |
| Plasma Instabilities, Energetic Particle Precipitation | Emissions, Radiowave Phase & Amplitude Variations | ELF/VLF Receivers, Scintillation Receivers |
| Conductivity Variations | Schumann Resonance | ELF Receivers |
| | Phase and Amplitude Perturbations | Incoherent Scatter Radars |
| | Local variations | Conductivity Probes (balloons) |

other countries. It is expected that the financial burden of such international components will be shared by the participating nations.

In this section the main requirements for new, state-of-the-art features of GEM instrumentation are discussed.

3.3.1 All-Sky Cameras

Fast and sophisticated processing of auroral images requires that film-based photography be replaced by electronic systems. An innovative approach is greatly encouraged for the construction of new auroral imaging systems capable of providing precise quantitative information. For practical purposes, however, a combination of both highly sophisticated digital all-sky cameras and much less expensive video cameras will have the highest scientific return. A state-of-the-art image processor is also needed to study the video tapes thus obtained.

3.3.2 Magnetometers

Modern ring-core flux-gate magnetometers of the type used on MAGSAT have noise levels 2 orders of magnitude less than the conventional flux-gate magnetometers deployed during the IMS. The noise levels are such (approximately 0.01 nT) that for some applications they can also replace the search-coil magnetometers used to record higher frequency (greater than 0.1 Hz) ULF waves. Ring-core magnetometers have just begun to be used in ground-based observations. The vast improvement in computer technology over the past decade also means that magnetometers can be economically equipped with far more sophisticated data recording systems, that will permit rapid data processing on site and faster data transmission. For higher-frequency wave studies, on-line systems can be built that will analyze the data in real time and only record intervals containing signals with characteristics chosen by the experimenter.

3.3.3 ELF and VLF Detectors

Traditionally, the electrical conductivity of the middle atmosphere has been measured experimentally using long-duration balloon measurements at altitudes up to approximately 40 km. Sounding rockets can provide short duration, but more complete, measurements in the ionosphere. A new technique that offers the possibility of continuously monitoring changes in middle atmosphere conductivity uses the global properties of the electromagnetic normal modes of the earth-ionosphere cavity, the so-called Schumann resonances. These resonances are excited continuously by naturally-occurring lightning. Each cloud-to-ground lightning stroke sets up a combination of standing and traveling waves whose wavelengths are integral submultiples of the planetary circumference. The lowest Schumann resonance eigenfrequency is approximately 7 Hz, with 7 or 8 harmonics typically excited within the earth-ionosphere waveguide. The earth-ionosphere cavity is, in effect, a planetary sized "whispering gallery" wherein an excitation from lightning at any point produces a signature observable at any other point within the cavity.

At low ELF frequencies, the atmosphere becomes resistive at an altitude of roughly 50 km. Thus, for the case of Schumann resonances, the ionosphere begins in the middle atmosphere. Dynamic changes in the conductivity within

this region are therefore manifested as modulations of the waveguide resonance characteristics that may be observed using ground-based instruments. Because of the global nature of the resonance, a relatively small number of ground stations can be used to monitor these modulations.

Ground-based measurements of the amplitude and phase of subionospheric VLF/ELF signals have also been established as a sensitive means of studying energetic particle precipitation from the magnetosphere. High resolution measurements of multiple signals arriving at a receiver on a variety of great circle propagation paths allows the detection and measurement of wave-induced burst precipitation effects occurring over disturbed regions overlying the signal paths. The technique is particularly sensitive to precipitating electrons with greater than 40 keV energy, penetrating to the lower ionosphere and mesosphere and generating secondary ionization which, in turn, alters the earth-ionosphere waveguide mode structure of VLF/ELF signals.

3.3.4 Radars

Ionospheric electric fields can be measured from the ground using radar techniques. The standard bearer of this approach is the incoherent scatter radar which is capable of measuring line-of-sight plasma motions. By combining Doppler measurements from different viewing directions, it is possible to determine the ionospheric plasma drift and from it to derive the ionospheric electric field. In addition to providing this information, incoherent scatter radars provide information on basic ionospheric parameters such as current densities and temperature, thermospheric winds and particle and field energy deposition.

The second approach to electric field studies from ground is the coherent scatter radar. This technique requires small-scale ionospheric structures, irregularities, to backscatter the radar signals. In general, radar signals must be directed approximately perpendicular to the magnetic field lines; in the case of VHF systems, the irregularities that are observed are located in the E-layer of the ionosphere and produced by plasma streaming instabilities. These irregularities are only produced if the electric field is reasonably large, approximately 15 mV/m. Furthermore, as the magnitude of the electric field increases there is a tendency for it to be underestimated. In the case of HF radars, both E and F region irregularities are observed. The latter class of irregularities shows no evidence of requiring a threshold electric field for its generation. Furthermore, recent studies have demonstrated the consistency between plasma drifts measured with an incoherent scatter radar and F-region irregularity drifts measured with an HF coherent scatter radar. Both HF and VHF backscatter radar systems are limited by the fact that ionospheric irregularities are not present all the time. This restricts the season, geomagnetic activity, time of day and geographic location in which these instruments can provide information relevant to GEM.

Other emerging radiowave techniques may also hold promise for determining ionospheric electric fields. Scintillations of satellite beacon signals are produced by the same F-layer ionospheric irregularity regions that cause coherent radar backscatter. Ground-based spaced-receiver networks can sense these scintillations and it may be possible to deter-

mine the irregularity drift. Modern HF digital ionosondes are also equipped with spaced-receiver systems. These, too, may provide information on the net drift velocity of the overhead ionosphere and ultimately on the ionospheric electric field.

3.3.5 Riometers

In recent years, riometry has evolved from simple, but coarse, monitoring of energetic electron precipitation into an increasingly sophisticated technique capable of investigating the spatial structures and dynamics of precipitation regions in extensive detail. Instruments incorporating phased array antenna systems can now image ionization structures in the D and E regions of the high latitude ionosphere with temporal resolution of the order of one second and spatial resolution of the order of 10 km. These radio imagers, operating at frequencies in the 30-50 MHz range, provide continuous measurements and are not limited by optical sky brightness or weather conditions, a distinct advantage especially for conjugate studies.

3.3.6 Balloon-borne Instruments

Observations made from balloon platforms provide a valuable complement to the proposed ground-based investigations for studies conducted at high latitudes (cusp) and middle latitudes (middle atmosphere coupling).

Neither the energetic electrons that enter the atmosphere, nor the X-rays that they produce, can be measured at the ground. However, balloon X-ray (and photometric) measurements including the use of imagers, can provide information on the wide range of spectral, temporal and spatial variations present in the precipitated electron fluxes. Detailed comparisons between photometric and X-ray data provide information on the characteristics of the ionospheric and magnetospheric acceleration mechanisms. Inclusion of electric field, VLF, and magnetic field instruments would yield additional information on convection, VLF wave activity, motions of precipitation sources, and the dynamics responsible for ionosphere-magnetosphere coupling.

Stratospheric balloon-borne techniques for measuring vector electric fields and conductivity have been used successfully for two decades. It is now well established that at middle and high latitudes in fair weather, the horizontal electric field at balloon altitudes very nearly represents a one-to-one mapping of the large scale ionospheric electric field. Focused campaigns of multiple short-lived zero-pressure balloons have successfully measured the global and polar convection patterns with relatively coarse spatial resolution. It has been demonstrated that the corresponding instruments can be successfully flown on superpressure balloons. These balloons were developed for the NSF-sponsored Carrier balloon project in which average lifetimes of over one month at 26 to 28 km altitude were achieved. It is now feasible to double or triple the number of simultaneous flights for vector electric field measurements.

3.4 Coordinated Observing Campaigns

Significant advances in understanding the electrodynamics of the atmosphere-ionosphere-magnetosphere system can be achieved by means of coordinated, limited-duration Observing Campaigns aimed at solving specific physical

problems. They would involve deployment of new instruments and simultaneous measurements from the ground and from balloons, as appropriate. The four Observational Campaigns proposed for GEM are described below.

3.4.1 Ionosphere Signatures of Magnetospheric Cusp Processes

A major observational effort should be directed toward achieving a quantitative understanding of the coupling between the solar wind, magnetosphere and ionosphere (see Section 3.2.1). This coupling process begins at the dayside of the magnetopause where the solar wind first encounters the geomagnetic field; it involves electric currents which flow from the interaction region to the ionosphere along geomagnetic field lines. The spatial distribution of these currents, their strength and their dependence on the solar wind and the interplanetary magnetic field are only partially understood.

Because of these field-aligned currents and other transmission processes along field lines such as Alfvén waves, the solar wind-magnetosphere coupling processes occurring far out in space lead to phenomena in the ionosphere that can be “remotely sensed” from the ground, balloons or aircraft. Project GAMBLE (Ground-Airborne Magnetic Boundary Layer Experiment) will consist of coordinated measurements of relevant ionospheric parameters in the region that is magnetically connected to the dayside magnetopause. The parameters of interest include the currents, the ionospheric electric fields and conductivities, and the configuration of particle precipitation boundaries. GAMBLE will be planned to unfold in time with campaign-mode peaks of activity determined by the best intervals for optical observations, combined with a year-round level of activity involving observational techniques which do not depend on sky background darkness and weather.

In order to assess the relative importance of the various physical processes which have been proposed for magnetic reconnection at the magnetopause, it will be necessary to observe the ionospheric signatures of solar wind-magnetosphere interaction with a high resolution in time and space. A dense network of ground-based observatories under the midday part of the auroral oval should provide the principal information. The auroral features, for instance, may be observed optically from stations located in areas of sufficiently high geographic latitude (greater than 75°) to be dark during the day in winter, yet that are of low enough geomagnetic latitude to be frequently under the dayside cusp position at geomagnetic noon (approximately 75° invariant latitude). This condition is satisfied at several existing observatories on the islands at the edge of the Arctic Ocean north of Norway and the western Soviet Union. A series of multinational programs of northern winter optical observations has already been carried out since 1978 on Svalbard.

A new 3-year international program of ground-based and airborne observations, concentrated around Svalbard and the surrounding area (the Greenland Sea and Barents Sea) is proposed for GEM. The main observing stations for this program are shown in **Figure 5**. The Svalbard-centered stations presently have an all-sky film camera, a riometer, and a magnetometer. New all-sky (video) cameras and ring-

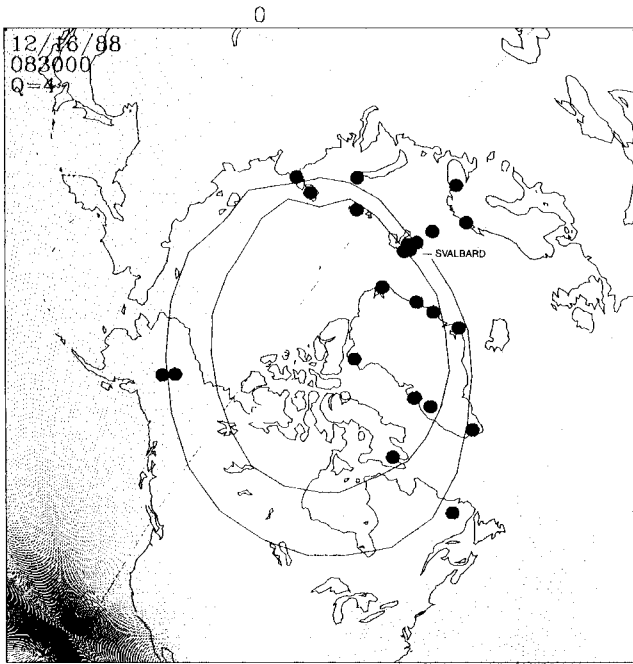


Figure 5: Observing stations proposed for the study of ionospheric signatures of magnetospheric cusp processes. Circles: Svalbard-centered GAMBLE (Ground-Airborne Magnetic Boundary Layer Experiment) network of optical and magnetic observatories, and participating radar, riometer, optical and magnetometer stations. The auroral oval is shown for noon at Svalbard in winter.

core magnetometers will be strategically distributed in such a way as to optimize detection of optical features and magnetic signals associated with non-steady reconnection. The Alaska stations will monitor auroral conditions in the night sector when Svalbard is on the dayside, thus allowing the separation of plasma entry events from other auroral phenomena.

Simultaneous studies of solar wind/magnetosphere coupling effects will be conducted with the incoherent scatter radar in Sondrestrom, the cluster of ground-based instruments around it and the two magnetometer arrays in the east and west coasts of Greenland (Figure 5). Additional magnetometers placed in the interior of Greenland would complement the existing set of instruments, by forming a dense array to identify localized events near the dayside convection reversal boundary.

Imaging riometer systems should be considered for deployment at Sondrestrom, Greenland and at Frobisher Bay, Canada (the nominal magnetic conjugate point to South Pole where such a system is now in operation). Specific goals of the riometer program would be to delineate the characteristics of the energetic component of the particle precipitation associated with flux transfer events (FTEs) occurring on the dayside magnetopause. Preliminary results of recent conjugate point measurements with broadbeam riometers and fluxgate magnetometers at South Pole and Frobisher Bay

indeed suggest that an energetic particle component is associated with at least some possible FTE signature.

Finally, recent balloon measurements above South Pole indicate, too, that energetic electron precipitation is a persistent feature on geomagnetic field lines near local noon that map to (or near to) the dayside cusp and magnetopause region. It is thus important that balloon measurements also be included in the GAMBLE project.

3.4.2 Global Substorm Features

The magnetospheric substorm represents the principal large-scale transient process in the chain that couples energy from the solar wind to the terrestrial atmosphere. Although substorms have been studied extensively in the past, there remain many unanswered questions of a fundamental nature.

One such problem is understanding the global current system linking the magnetotail and the ionosphere. The distribution of substorm-related field-aligned currents can only be inferred on a continuous basis from ground-based measurements. A subauroral magnetometer chain is the most cost-effective way of monitoring these currents; it can provide essential information on the timing, location and evolution of a substorm, especially if the data rate is sufficiently high to allow the recording of $\pi 2$ pulsations, because the latter can provide the most reliable timing signature of substorm onsets and intensifications. Moreover, their polarization pattern, when observed on a longitudinal chain, yields important information on the spatial configuration of the substorm.

The advantage of subauroral over auroral magnetic data is that the gross features of the currents are not masked by local details. An auroral zone magnetometer responds primarily to the auroral electrojet about 100 km overhead; hence, the main signal comes from currents flowing within about 100 km of the magnetometer site. An auroral zone network spacing of about 100 km would be required to determine the complete ionospheric current pattern—a task logistically impractical. Subauroral magnetometers, on the other hand, respond to currents over a much larger scale, and a coarser grid will be sufficient to determine the global pattern of current flow.

The North American continent could be spanned by a longitudinal chain of seven magnetometers at subauroral latitudes (55-60 deg, $L = 3-4$) extending from southern Alaska to Newfoundland. This chain would cover about 8 hours in MLT with a station spacing of 1-2 hours. A possible scenario is two stations in southern Alaska, four stations across the continental U.S. and one in Newfoundland. Canadian scientists are building a higher-latitude network of magnetometer and riometer stations in the North American sector (project CANOPUS). The chain proposed here would extend this network to subauroral latitudes; the Newfoundland site would provide a link to European networks, and one of the Alaskan sites could be chosen to be magnetically conjugate to a New Zealand station, thus linking the chain to the west. Cooperation with other U.S. agencies (U.S.G.S., Air Weather Service) which maintain existing or are planning new magnetometer networks, would help keep costs to a minimum. Each site would be equipped with a

ring-core-flux-gate magnetometer and a microcomputer-based data recording system. The routine data sampling frequency would be on sample every 3-5 sec, but the recorders would have the capability of much faster recording rates to be used on a campaign basis.

The subauroral magnetometer chain would complement observations of the cusp region, such as those outlined the GAMBLE project. The studies of the polar cusp will be concentrated in the Greenland-Svalbard area, which passes through local noon when the proposed subauroral magnetometers are on the nightside providing simultaneous monitoring of nightside substorm activity. By combining these two data sets, changes in the cusp that are due entirely to IMF changes can be differentiated from those due to internal magnetospheric processes. Understanding the changes in the transpolar cap convection pattern observed by the instruments described in the previous section will also be made easier by having simultaneous observations of substorm activity provided by this chain.

As a direct aid to the Theory Campaign on Global Modeling of the Magnetospheric B-field (Sec. 2.3.3.) conjugate point measurements at auroral and subauroral latitudes are also very important. The similarity of upper atmospheric phenomena such as auroral displays and magnetic variations at two points connected by a single magnetic field line has attracted the attention of researchers since the early days of magnetospheric physics and remains an important aspect of magnetospheric-ionospheric research today. With greatly improved ground-based instruments, it is now possible to advance further and examine the degree of conjugacy in a detailed quantitative way as a function of local time and latitude. Observing high frequency phenomena, such as VLF, ULF emissions and rapid auroral fluctuations, as well as employing radio imaging techniques that are not limited by sky brightness or weather conditions, may be particularly useful. Since experimental methods to trace field lines over great distances are not well established and could not provide continuous information, a ground-based study might yield clues as to whether, at any given time, a particular field line is closed across the neutral sheet in the magnetotail, or whether it is open. This may be accomplished by choosing two conjugate pairs at different latitudes, on pair slightly poleward of the auroral oval and the other inside.

3.4.3 Global Convection Pattern

The total number of ground-based instruments capable of measuring high latitude convection is still very small. Currently, the list is comprised of three incoherent scatter radars (EISCAT, Sondre Stromfjord, Millstone Hill), three HF coherent scatter radars (Goose Bay, SHERPA, PACE), and three VHF coherent scatter radars (STARE, SABRE, BARS). All of these radars are located in the northern hemisphere, with the exception of PACE whose field of view is magnetically conjugate to that of Goose Bay.

While these instruments provide an extremely valuable source of data, their coverage is insufficient to yield the instantaneous large-scale convection pattern that is sought withing the GEM initiative. Additional capabilities are clearly needed. Ideally, the new instruments could be

grouped to form a meridional line across the polar cap and the auroral zone, allowing an estimate of the polar cap potential drop. A possible system would include instruments at Tromsø (EISCAT, STARE), Svalbard, an Thule. At lower latitudes, it would be supplemented by sites in Scandinavia such as Uppsala, and by Canadian and Alaskan sites. This chain would be nearly perpendicular to the existing radar chain that extends along a meridian from Sondrestrom through the Goose Bay HF radar field-of-view to Millstone Hill. Thule, almost at the intersection of these two axes, would be a key location for additional instruments, extending the existing coverage to a large portion of the polar cap and auroral zone.

Whether the new capabilities are based upon incoherent scatter radars, coherent scatter radars, or some new approach such as supplementing gaps in the existing radar chains by adding several new HF Doppler radars, certain conditions must be met if they are to contribute effectively to the scientific goal of GEM. The measurements must be truly global in nature and continuous in time, they must have temporal resolution of 5 minutes or less, and they must lead to accurate determinations of the electric field pattern. Moveover, the approach must be practical as well as economically balanced within the overall GEM program.

3.4.4 Magnetosphere-Atmosphere Electrodynamic Coupling

(i) Schumann Resonance Measurements

The global nature of the Schumann resonances offers the opportunity to determine two types of parameters of interest to the understanding of solar-terrestrial physics. The first is global lightning activity. Despite being one of the oldest of natural phenomena to be studied systematically, the detailed spatial and temporal distribution of lightning remains only partially documented. Systematic monitoring of the intensity of Schumann resonances can be used to derive a quantitative measure of the average, global rate of lightning discharges for input into studies of the global electrical circuit.

The dependence of the cavity resonance characteristics on the detailed two-dimensional lateral distribution of conductivity within the mesosphere suggests that Schumann resonances can also be used to monitor changes in the conductivity at these altitudes. Thus detailed measurements of discrete Schumann events may contain the information needed to determine the effective height, as a function of geographic position, of the lower D-region where the atmosphere becomes resistive. This technique would enable the formation of two-dimensional "images" of the mesospheric conductivity. By monitoring the changes of the conductivity, it would be possible to detect and follow modulations of the conductivity occurring from external sources. Such sources include galactic and solar cosmic rays and energetic particles precipitated out of the magnetosphere. Coverage would be synoptic and global.

The cost of instruments required for both global lightning coverage and global imaging of the D-region conductivity is relatively modest. The basic measurements can be provided by 4-6 globally distributed ground stations, each of which monitors the two components of horizontal magnetic and

vertical electric fields over the frequency band of 1-100 Hz. The sensors and instrumentation needed for these measurements exist and do not require extensive additional development. A successful program could be implemented immediately using currently available technology.

(ii) VLF Network for Wave-Induced Particle Precipitation Studies

In view of its capability for simultaneous observation of large regions, the sub-ionospheric VLF/ELF technique promises to be a useful complement to spacecraft, balloon or rocket-borne observations to investigate the large-scale nature of lightning-induced precipitation of energetic particles and the role of these particles in determining the conductivity of the night-time D-region. To fully exploit this VLF/ELF technique for measuring transient and localized perturbations of this region, it is proposed to make measurements at 8-10 sites in the northern hemisphere. Up to 4-5 of these sites would be distributed within 500 km of one another around a region of known high occurrence of lightning. Possible locations in the east coast of the U.S. would include Florida and Wallops Island, Virginia (for coordinated campaigns with balloons).

The rest of the receiving sites would be distributed with larger separations, with the goal of investigating the large-scale distribution of events and assessing the occurrence and characteristics of lightning-induced electron precipitation as a function of longitude and latitude. In view of the recent observations of lightning-associated perturbations occurring at L less than 2, the observations at low latitudes under the inner radiation belt are particularly important. In order to assess the importance of direct energy input to the upper atmosphere and ionosphere due to thunderstorms, coordinated experiments should be devised to measure the electrodynamic a.c. and d.c. output of thunderstorms in conjunction with ground-based atmospheric electrical and mesospheric-ionospheric measurements (rockets, radars and satellites). Recent pioneering efforts have demonstrated that lightning transients result in an electric field signature in the ionosphere (up to at least 150 km) lasting longer than 5 milliseconds with components both parallel and perpendicular to the local magnetic field, of amplitude one or two orders of magnitude above the quiescent ionospheric field. The effects on the collective plasma phenomena in the ionosphere and indeed even the level of total energy input are not

TABLE 5
**OBSERVATIONS AND MEASUREMENTS
BUDGET OUTLINE
(IN K\$)**

| | '91 | '92 | '93 | '94 | '95 | '96 |
|--|-------------|-------------|-------------|-------------|-------------|-------------|
| Ionosphere Signatures of Cusp Processes (1) | 770 | 845 | 570 | 570 | 570 | 570 |
| Global Substorm Features (2) | 230 | 605 | 430 | 380 | 380 | 380 |
| Global Convection Pattern (3) | | 300 | 600 | 1050 | 950 | 850 |
| Magnetosphere-Atmosphere Electrodynamic Coupling (4) | | 150 | 400 | 870 | 870 | 820 |
| TOTAL | 1000 | 1900 | 2000 | 2870 | 2770 | 2620 |

- 1) Includes new facilities for ASI, magnetometers, riometers and use of existing radar facilities.
- 2) Includes magnetometers and conjugate pair measurements (which also contribute to 1 and 3).
- 3) Includes new radar or ionosonde facilities and balloon E-field and X-ray measurements.
- 4) Includes ELF, VLF and balloon E-field measurements.

yet known. It will require coordinated experiments involving all known techniques to determine the importance of thunderstorms to these ionospheric phenomena.

(iii) **Global Electric Circuit**

The third project is relevant to both middle atmosphere vertical coupling as well as solar wind-magnetosphere-ionosphere coupling processes such as convection (section 3.2.1). It will involve long-duration balloon flights to measure electrodynamic parameters in the stratosphere from multiple simultaneous payloads. As mentioned before, balloon-borne measurements of the electric field and conductivity have been very useful in helping to investigate large scale polar electrodynamic phenomena. Most of these previous experiments used short lifetime balloons and focused on specific problems addressable with short (less than 1 week) data sets. Recently this well-known technique has been applied to superpressure balloons which have lifetimes averaging more than one month. Through satellite communication relay the data can be monitored in real time from anywhere on earth. It is proposed to use superpressure balloons to make the in-situ measurements necessary to study vertical coupling problems.

These superpressure balloon payloads are similar in many respects to short life-time satellites and are complementary to the ISTP program which has no low-altitude satellite component. Thus, this superpressure balloon experiment can in addition provide foot-of-the-field-line data during the ISTP mission. Furthermore, since the flights are only possible in the southern hemisphere (for political reasons concerning overflight) these data will be complementary to the convection electric field project (Sec. 3.4.3).

3.5 Budget

Table 5 presents the proposed total budget allocations by fiscal year for each of the four coordinated observing campaigns. Representative costs for equipment, operating expenses, travel, research and project coordination have been figured into these budgets. These estimates have been based on a preliminary assessment of the core facilities that would be required and that are likely to be proposed.

The first observing campaign, for example, may involve the placement of magnetometers, all-sky optical and radio imagers at select locations, and the use of existing radar facilities. The project on Global Substorm Features may involve the placement of additional magnetometers as part of a new longitudinal chain. The conjugate point component of this project (see 3.4.2) might be accomplished by a judicious placement of stations used in the GAMBLE project with some augmentation of equipment. A combination of radar and ionosonde techniques, both existing and new, would likely form the backbone of the Global Convection project. However, support for coordinated balloon electric field and X-ray measurements has also been included. Lastly, the Magnetosphere-Atmosphere Electrodynamic Coupling project incorporates a combination of ground radio and balloon electric field measurements pertinent to the study of global conductivity, wave-induced particle precipitation and the global electric circuit.

Expenditures for the acquisition and installation of ground-based equipment are emphasized in the first 1-2 years of a project. Where balloon experiments are involved, maximum expenditures occur in the 3rd or 4th year. Research costs primarily related to data analysis dominate the later years. Each campaign in principle, has a nominal termination date for the data-taking phase. However, some operating funds are included to continue data-gathering activities beyond this date where the measurements would support the other campaigns in progress.

CHAPTER IV:

Data Analysis and Information Systems

4.1 Introduction

Since the International Geophysical Year in 1957-1958, solar-terrestrial data collections have evolved from being primarily ground-based in origin to including large satellite data sets, and from being mostly analog and tabular to computer-accessible digital data. Major changes have also taken place in the approach to solving scientific problems. Today, few problems in solar-terrestrial physics can be solved by an individual scientist analyzing data from a single instrument. The complexity of the problem determines the extent of the required data base, which may span data from several instruments on one satellite to data from several satellites plus a variety of ground-based observations. The accumulation of multiparameter data sets is a necessary step in attacking the major scientific problems of solar-terrestrial physics, now being pursued by the NASA Global Geosciences Program (GGG), the trilateral International Solar-Terrestrial Physics program (NASA/ESA/ISAS, 1984), and the worldwide Solar-Terrestrial Energy Program (SCOSTEP, 1986a). The issues related to the complicated solar-terrestrial data sets have been addressed by several committees of the National Research Council of the National Academy of Sciences (NAS/NRC, 1982; 1984 a and b; 1986; 1987). A parallel effort associated with data collected by the aeronomy community is being conducted as part of the Coupling, Energetics and Dynamics of Atmospheric Regions Program (CEDAR, 1987).

The Challenger disaster has caused a rethinking by many space science disciplines of how best to conduct their research and pursue their pressing scientific problems. Not only do expendable launch vehicles and smaller less-expensive satellites present an attractive alternative for the space segment of this research, but the value of existing data, space and ground-based, is much more appreciated. Recent technological advances in data processing, storage and retrieval, and presentation have been staggering. The time has come to begin the application of modern data-handling techniques and strategies to the existing bank of solar-terrestrial data for the purpose of extracting possible new scientific insights and solutions to the present problems as well as providing stringent tests for newly developed theories, models and hypotheses. An important by-product of this effort will be to provide the experience necessary to efficiently use data to be collected by future programs such as GGS, ISTP and STEP, whose data collection phase is still several years away.

The cost of modern data facilities has been reduced to a level that is affordable to almost every educational institution. Solar-terrestrial data sets are already beginning to be introduced into the undergraduate educational process. In the following sections, NSF initiatives in Data Analysis and Information Systems are proposed that will exploit present technological advances to maximize the return from existing

data archives and to prepare the community for the new observations that will flow from future solar-terrestrial programs such as ISTP and STEP.

4.2 Initiatives

A productive attack on scientific problems requires access to relevant observations. General access to data requires catalogs and directories that describe the data maintained in data bases, data libraries, and data archives. General use of the data requires standardization of formats and protocols that provide an easy use of technological capability to manipulate and display the data. The data needed to address problems in solar-terrestrial physics come from diverse sites and instruments. While expertise in handling and analyzing particular data sets often lies in the hands of a limited number of researchers, that same data is needed by a broad spectrum of users. To optimally manage, distribute, and analyze these data, we recommend five new initiatives: (i) the creation of Discipline Data Centers; (ii) the utilization of electronic networking; (iii) the application of new data-handling technology; (iv) the utilization and dissemination of computing resources; and (v) the use of solar-terrestrial data in the educational process. Although we have stressed experimental data in the discussion above, the five initiatives proposed apply equally as well to computer simulations and modeling efforts.

4.2.1 Discipline Data Centers

Solar terrestrial data commonly are found in one of three types of data management units: data repositories, active data centers and data archives (see, for example, Section 1B of the National Research Council CODMAC Report, NAS/NRC, 1986). An example of a data repository is an incoherent scatter radar site that maintained a collection of data obtained in different observing periods. An example of an active data center is an institution that collected all-sky camera observations from around the world, cataloged them, checked them for quality and used them to study the nature and dynamics of auroral forms. An example of a data archive is the World Data Center A for Solar-Terrestrial Physics which archives, among many other data sets, the worldwide observations of solar flares and makes them available to requestors. We note that the lines between these units are not always distinctly drawn and that a particular site might have some characteristics of two or more of these types of data-management units.

Ultimately, most solar-terrestrial data that becomes permanently archived is stored in either the World Data Center A for Solar-Terrestrial Physics which is managed by NOAA, or the National Space Data Center (NSSDC) which is managed by NASA. Which center is used is determined principally by the agency of origin of the data. Most solar-terrestrial data acquired by NASA, or in space by foreign

governments who choose to exchange data with NASA, are stored in the NSSDC. Most data acquired by ground-based observers or non-NASA U.S. spacecraft are held by the WDC-A for STP. Most frequently, data obtained in campaigns are not archived. Only the routine synoptic data are maintained.

Data repositories are usually supported as part of the resources allocated for data-gathering. However, seldom does this data-gathering support provide for directories and catalogs, standardization of formats and documentation, dissemination of data or assistance to the untrained user. These functions are provided usually only by active data centers in which a cadre of expert users has been built up in active utilization of the data for scientific purposes. As stated by the Joint Data Panel of the National Research Council's Committees on Solar and Space Physics and Solar-Terrestrial Research (NAS/NRC, 1984b), "...scientific involvement in data system planning, in data processing, and data distribution is essential." For this reason, a successful scientific program must involve sites with active expert users. We call such a site a Discipline Data Center.

A typical Discipline Data Center (DDC) would be established at a location such as a university or laboratory in which a group of active researchers were engaged in the use of solar-terrestrial data. It should be structured with an outside advisory committee of researchers from other institutions who could judge the success of the effort and guide its development. The DDC would develop catalogs and directories to the data base, increase the holdings in the data base to the extent possible, taking care to acquire and curate only usable data. The DDC would apply data quality checks and develop standard data formats. It would also provide access to the data and aid in its dissemination. It would provide assistance to untrained users.

The DDCs would be divided into two general categories: problem-oriented and data-oriented. The problem-oriented DDCs will be associated with the major experimental and theoretical GEM programs. The problem-oriented DDCs would provide the data base necessary for the GEM Theoretical Campaigns and could serve as the mechanism to bring together the communities of theorists and experimentalists. These DDCs could build on the experience gained in the NASA Coordinated Data Analysis Workshops (CDAW) and provide the background for the National Solar-Terrestrial Research Program (NAS/NRC, 1984a). Examples of scientific topics which could be supported by problem-oriented DDCs would include global patterns of polar plasma convection, ionospheric currents, and cusp phenomena.

The data-oriented DDCs could be centers for surface magnetic field observations, coherent radar systems, ground-based imaging (all-sky cameras and photometers), riometers, ionosondes, active and passive VLF and ELF recordings, and non-NASA satellite data. The last category would include particle, magnetic and electric field, and imaging data available from several non-NASA satellites, for example from DOD and NOAA.

We recommend that similar efforts be initiated in the areas of all-sky cameras, ground-based magnetograms, and satellite auroral imagery. We envision that these DDCs

would be geographically distributed but electronically connected and that their catalogs would be maintained on-line. Such DDCs could sponsor workshops analogous in many ways to the CDAWs, but perhaps of more limited scope. The DDCs also would participate directly in the larger-scale STP programs such as GGS, ISTP, and STEP.

4.2.2 Electronic Communications

Electronic communication now provides a means to bring major capabilities and facilities to remote researchers at institutions that are resource-limited. Among the capabilities that electronic communication provides are remote log-on to computer systems, mail and file transfers. File transfers must include the movement of data, plot files, and manuscripts.

For this initiative, computer-to-computer communications provides a flexible infrastructure for data and information access and exchange that is essential for correlative NSF solar-terrestrial research. The communication network sponsored by NSF called "NSF-Net" has the necessary capability to support the desired communications. We recommend that NSF-Net should be the communication cornerstone of the new GEM program. This capability has the important advantage that there is at least one major link or gateway from NSF-Net to the NASA Space Physics Analysis Network (SPAN) that already connects much of the solar-terrestrial research community.

A Discipline Data Center (DDC) must be able to support access by the NSF-STR community and therefore must be connected into NSF Net and Telenet at a minimum. This access would include online data catalogs, inventories and software libraries. It is important to note that, in addition to computer communication to the DDCs, NSF-STR centers also should be networked together thus providing a base level of connectivity for the entire science community.

4.2.3 New Technology

Present solar-terrestrial research often demands a multi-parameter data base that usually must be assembled from data elements found in widely distributed, individual data sets. Because of this, major problems have arisen in solar-terrestrial research in the areas of easy access to these distributed data elements; merging them into a larger data base; access (distribution) of this larger data base by (to) interested researchers; and common display of the data elements and their correlation. The impact of simulation and modeling programs has not only increased the requirements for rapid computation, but also for interactive graphics techniques to effectively visualize the results of these complex computations. Available and imminent new technologies are making major progress in solving these problems, and we recommend that the NSF aggressively pursue a new technology initiative in the GEM program to optimize the use of solar terrestrial data by establishing the means for easy data access, efficient data use, and improved visualization techniques by appropriate NSF-funded researchers.

Expanded personal computer capability, WORM (write once, read many) disks, compact disks, digital video tape, data base management systems, graphics systems, and computer-to-computer networking are examples of new hardware and software technology becoming available at an

increasing pace and decreasing cost. Most, if not all, of these advances bear directly on problems solar-terrestrial data access and use. For example, the use of WORM disks with personal computers will allow small research groups to participate fully in most major solar-terrestrial research programs. The required data bases may be assembled by the research groups directly via the NSF-Net or obtained from larger central data repositories.

The human visual apparatus is still the best pattern-recognition system available. New, unanticipated conclusions often are obtained when experimental data or theoretical output is organized into formats that make new aspects of the data stand out visually. It is essential to be able to experiment with a wide range of visual presentation techniques to optimize the chances of spotting totally unexpected correlations between elements of the extremely complex multidimensional experimental and theoretical data sets that commonly are encountered in solar-terrestrial research. Most of the exploratory work in data visualization and presentation can be carried out on relatively small work-stations. Some of the final summary presentations may require the use of expensive computer animation equipment which is justified only on the largest supercomputers, so that it can be shared by many groups.

The NSF should require that proposals for programs generating major data bases include well-defined data collection, processing and access provisions. The NSF should fund programs to acquire, test and evaluate new technologies for data access and use. Finally, the NSF should evaluate the possibility of acquiring a number of standard data-accessing systems to be made available to NSF projects in order to implement an active data access and exchange process.

4.2.4 Supercomputing Resources

Supercomputers are essential for most large theoretical kinetic plasma and MHD simulations. In the new initiatives, proposed in other sections of this report, supercomputers will be required to unfold or invert large experimental data sets. A third use of supercomputers involves projects with complex presentation requirements. We recommend that the GEM program take full advantage of the resources to be made available as part of the NSF Supercomputing Initiative.

Theoretical projects often involve intercomparisons between linear or nonlinear analytic work, particle or MHD models and simulations, and possibly experimental data. The analytic portion frequently makes use of smaller computers to solve differential equations, while simulations typically require the supercomputers. It is anticipated that supercomputer access will continue to be an integral part of many new theoretical initiatives. In addition, it is anticipated that an increasing fraction of the new observational initiatives also will require access to supercomputers. Some large data sets will require extensive computer processing before they become useful to the community. For example, raw data from radars, ionosondes or magnetometer chains may be of limited use to a specific study, while the electric field, plasma flow, electric current density, or conductivity model that is obtained after processing the data may be extremely useful, either as input to a global model or for

comparison with the output of theoretical simulations and modeling.

The National Science Foundation has an existing super-computer network which can be used for new solar-terrestrial research projects. Useful access to this network may require funds for the purchase and support of networking equipment in new proposals. The costs to upgrade network equipment, and of maintenance should be shared among all projects at any one institution that requires super-computer access.

4.2.5 Education

The fact that Solar-Terrestrial Physics has, and will continue to collect a large data base offers an excellent and inexpensive opportunity to attract young students to, or at least make them aware of, this field of study early in their careers. This can be done effectively by making STP data available to educational programs in easily accessible formats and on media commonly available for personal computers. Such data may be used in a variety of educational programs thereby providing exposure of the solar-terrestrial research field to young students across a broad cross-section of the college (or high school) curriculum. For example, at Gallaudet College, a physics summer school for handicapped honor students was provided Sunspot Numbers on floppy disks. Through hands-on experience in the summer school, students learned to operate a personal computer, plot simple graphics, compute statistics, and test theories. This was the first instance of a data set at the servicing data center being transferred down onto a floppy disk. The following year, the experiences of that workshop were used as the basis for a course for physics faculty from several universities.

We recommend that under the auspices of the GEM program, the NSF initiate cost-effective procedures as described above to increase the awareness of solar terrestrial research to students early in their educational career. Resources should be made available for Data Repositories, Data Archives and Discipline Data Centers to transfer appropriate portions of selected data bases onto floppy disks and make them inexpensively available to schools. The disks should be accompanied by suitable access and display codes prepared by the providing center. Staff from the centers and research scientists involved in STP programs should be available to speak to student groups and to illustrate to them the interesting, dynamic range of STP phenomena and the data by which they are studied. This represents one method through which there may be kindled in young students an abiding interest in solar-terrestrial phenomena that will lead to their entrance into more advanced studies in the field.

4.3 Budget

A budget was developed for a six-year initiative in Data Analysis and Information Systems with the following strategy. It is anticipated that the largest fraction of the cost would be used to support the development of the Discipline Data Centers (DDCs). A DDC should include the following elements: Processors, Interactive Front Ends, Communicators, Data Base Management Systems, Mass Storage, Software Packages, Display and Graphics Tools, Interactive

Terminals, and Output Devices (printers, plotters, film). The support for personnel (such as software developers, scientists, and managers) and maintenance should also be included in the DDC cost. It is estimated that the minimum annual cost of a DDC, for example a Magnetic Field DDC, will be \$150K. The annual cost is estimated to be \$500K for a DDC for satellite imagery, for example.

We estimate that the cost to support the electronic communication initiative for the GEM program would be relatively modest. Some of the cost may be shared by other programs associated with the NSF-NET.

The cost to introduce new technology for the analysis of solar-terrestrial data is determined by the type of equipment that will be made available over the next four years. For example, expanded personal computers, work stations, stor-

age systems, graphics and display systems, and data base management systems are becoming available at an increasing pace and at decreasing costs.

We have recommended that the NSF initiate a program to increase the awareness of students to solar-terrestrial research early in their education. We believe that this can be accomplished at the relatively modest level throughout the GEM program. These funds would be used to transfer appropriate portions of selected data bases to floppy disks, to provide access and display codes, and to support visits by research scientists to various schools.

The total cost for the four elements of the Data Analysis and Information Systems portion of the GEM program is summarized in **Table 6**.

TABLE 6

PROPOSED BUDGET FOR DATA ANALYSIS AND INFORMATION SYSTEMS INITIATIVES (K\$)

| | '91 | '92 | '93 | '94 | '95 | '96 |
|---------------------|------------|------------|------------|-------------|-------------|-------------|
| DDCs | 150 | 300 | 450 | 950 | 950 | 1750 |
| Communications | 50 | 50 | 100 | 100 | 100 | 150 |
| Intro. of New Tech. | 200 | 200 | 200 | 250 | 300 | 300 |
| Education | | 50 | 50 | 50 | 50 | 50 |
| TOTAL | 400 | 600 | 800 | 1350 | 1400 | 2250 |

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