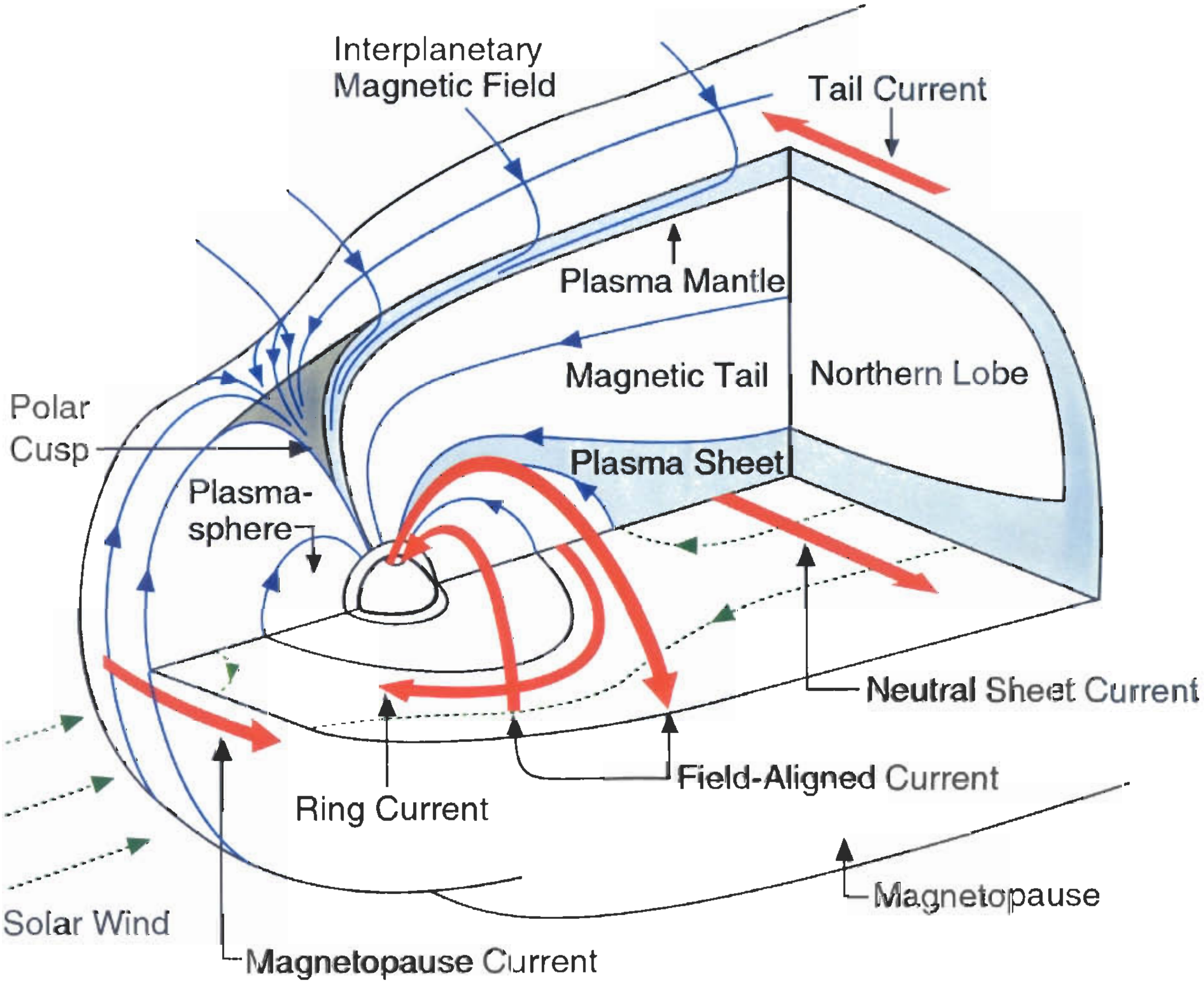
REPORT FROM THE FIRST GEOSPACE ENVIRONMENT MODELING (GEM) CAMPAIGNS: 1991-1997



Report from the First Geospace Environment Modeling (GEM) Campaigns: 1991-1997

Edited by C. T. Russell
from Contributions by
N. U. Crooker, R. A. Greenwald, M. Hesse,
M. K. Hudson, W. J. Hughes, L. R. Lyons,
N. C. Maynard, C. T. Russell, G. L. Siscoe and H. E. Spence

Published by
Space Science Center
Institute of Geophysics and Planetary Physics
University of California
Los Angeles,

October, 1999

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Foreword

In 1989 I attended my first GEM workshop, the Observational Campaign held at the University of Maryland. The energy and excitement that was being generated by the GEM community was infectious, and from that moment I knew that the one meeting that I absolutely had to attend every year was GEM. In the ten years since then my feelings have not changed in the slightest and the ever-growing size of the GEM meeting clearly shows that the rest of the magnetospheric community realizes the importance of the GEM workshops as well. Perhaps of equal importance to the future of our field, the GEM workshops have become an important educational tool for introducing students to magnetospheric physics. It has been our great good fortune that the GEM workshops have been organized by people who cherished both the research and educational ideals of GEM and have kept the workshops at the forefront of the exciting developments in our field. Although the total funding for GEM is only a tiny fraction of the total government funding for magnetospheric research, the GEM workshops, I believe, stand at the intellectual center. Our community owes a debt of gratitude to the various organizers of the workshops, who have done such a fine job of keeping the vision alive.

This report summarizes the history of GEM, results from the first two campaigns and the initial stages in the development of a Geospace General Circulation Model. I want to thank the many people who contributed to the report for an excellent job. They have distilled the excitement of the first seven years of GEM into a concise document that will be a useful guide to the work that has been done and a pointer for the future. I want to thank Dr. Chris Russell in particular for his work as editor of the report. Trying to get a group of physicists to work together on preparing a report like this has been likened to the job of herding cats. Chris obviously knows how to herd space physicists. Finally, I want to express my thanks to my predecessors in the Magnetospheric Physics Program at the National Science Foundation, who ultimately are the ones who made it all happen. It has been my pleasure to be associated with GEM as both a researcher and as the current NSF program director for Magnetospheric Physics. I look forward to a continued association with GEM for the remainder of my tenure at NSF and thereafter once again as a researcher.

Kile Baker, NSF
October 1999

Preface

The magnetosphere plays a key role in mediating the coupling between the solar wind and energetic solar particles and the Earth's upper atmosphere. The magnetosphere acts in part as a shield, in part as an energy storage device and in part as an accelerator in the energy chain. In our increasingly technological society both ground-based and space-based systems have demonstrated deleterious effects caused by disturbances in the magnetosphere. Thus it is imperative to understand the functioning of the magnetosphere and in the mid 1980's, Juan Roederer convened a workshop to formulate plans for a modest, yet innovative program of solar-terrestrial research. In 1991 the first funds for such a program became available and initial Geospace Environment Modeling (GEM) investigators and coordinators were selected. Because the available funding by itself could not achieve critical mass, much leveraging of existing programs was needed. Fortunately, the plan that developed, of focused campaign attacks on specific scientific targets of opportunity with annual meetings of key researchers, worked very successfully. Existing problems were solved and new problems could be addressed. A strong program ensued that continually re-invented itself and progressed to new goals.

The time has come to document that progress in other than just the scientific literature and in December 1997 C. R. Clauer, the director of the magnetospheric program of NSF's Atmospheric Sciences Directorate appointed the contributors to this volume to gather together the results of the GEM campaigns to date. In this volume we summarize the activities of the GEM community up to the time of our charter and indicate briefly the new directions GEM is setting for itself.

After a brief introduction the section on the history of the GEM programs, written by G. L. Siscoe and C. T. Russell, opens with a summary of the events leading up to the GEM program: the Seattle workshop where the master plan of GEM was developed and the following three pre-campaign workshops that established how the members of the GEM community would work together. The chapter outlines the conduct of the first two campaigns: the Boundary Layer Campaign and the Magnetotail/Substorms Campaign.

The next section written by L. R. Lyons, C. T. Russell and N. U. Crooker covers the activities of the Boundary Layer Campaign and its three working groups: Reconnection Electric Field and Magnetopause Boundary Normal Magnetic Field; Particle Entry, Boundary Layer Structure and Mapping; and Current Systems and Mapping. Each of these working groups worked in different fashions as befit the problems being solved. The first working group concentrated on ground-based data and event studies; the second concentrated on space-based data and discussions of outstanding problems; and the third had a mixture of format and data sources. All interacted strongly with modelers.

The second campaign, covering the magnetotail and substorms is described by N. Maynard, H. Spence and M. Hesse. This campaign consisted of three working groups: Onset Signatures; Magnetotail/ Substorm Phenomenology – Observations and Models; and Quantitative Magnetotail and Substorm Models. Again the working groups adopted varying styles of interacting as befit their areas of investigation. In 1997 the Magnetotail/Substorms Campaign was reconfigured and the working groups realigned. This phase of the campaign will be a subject of the next GEM report.

The next section of the report, prepared by G. L. Siscoe, discusses the evolution of thinking regarding the holy grail of the GEM program: the General Geospace Circulation Model (GGCM). The first part of this section describes the institutional history of the GGCM effort and how it evolved into a campaign of its own. The second part describes the detailed efforts undertaken by the campaign.

The report comes to a close by briefly reviewing GEM's new term strategy: the restructuring of the Magnetotail/Substorm Campaign; the beginnings of the Inner Magnetospheres and Storms Campaign; and the plans for a future Magnetosphere-Ionosphere Coupling Campaign prepared by L. R. Lyons, M. K. Hudson and R. Greenwald respectively. It then discusses briefly the essential ground-based program that has supported GEM and the educational component of the GEM program as summarized by W. J. Hughes. Appendices to the report include the Tables of Content of the six earlier reports on the GEM program; the strategic plan of the Inner Magnetospheres and Storms Campaign and a bibliography covering the science of the GEM Boundary Layer for the period 1990-1998.

We are grateful to G. Fasel and E. Zesta for providing some of the figures that illustrate the scientific results of the GEM program and to A. McGlynn and N. Pereira who aided us in the assembling of this report.

C. T. Russell
October, 1999

1. INTRODUCTION

The Geospace Environment Modeling program, GEM, is the second in order of inception of three programs that serve the solar-terrestrial community under the aegis of the Upper Atmospheric Research Section (UARS) in the Division of Atmospheric Sciences of the National Science Foundation. The oldest program, CEDAR, managed by UARS's Aeronomy Program, serves the aeronomy community. The newest program, SHINE, managed by UARS's Solar-Terrestrial Program, serves the solar/heliospheric community. GEM, managed by UARS's Magnetospheric Program, serves the magnetospheric community. A prime function of CEDAR, GEM, and SHINE is to provide a forum for the community each serves to interact annually for one week in an informal workshop setting. These workshops also provided excellent forums for graduate students to showcase their work. GEM has organized regular summer workshops annually since 1992, though as described in the historical sections of this report, preparatory workshops preceded it for several years. Besides annual workshops, GEM has a budget of about $500K per year within NSF's Magnetospheric Physics Program. Through annual competitions, this money is used to fund projects relevant to ongoing GEM campaigns.

GEM campaigns are a GEM innovation. Each campaign focuses like a spotlight on a specific region of the magnetosphere. Then, according to a preset program, GEM shifts the spotlight systematically from region to region in separate campaigns until the whole magnetosphere has been illuminated. Each campaign lasts four to five years, and two to three run simultaneously overlapping in time. The first campaign focused on the magnetosphere's boundary layers. The campaign was then divided among working groups that addressed specific topics of relevance to the overall campaign. Some working groups followed a more traditional approach of scientific presentation and discussion. These working groups assembled teams of experimentalists, modelers and theoreticians to consider problems of particular importance for which solutions seemed to be within reach. Other working groups concentrated on coordinated studies of magnetospheric events to further their understanding of specific phenomena. These became observational campaigns (both retrospective and prospective) within the overall scientific campaign.

The directions for the GEM program are set by a steering committee and the day-to-day operations performed by a set of GEM coordinators who manage the electronic and print communications, and the meetings that enable the science to proceed. In particular the Steering Committee decides when a campaign has run its course and when it is time to begin a new campaign.

While the campaigns were aimed at solving scientific problems, it was realized that the practical needs of society required that this scientific knowledge be captured in a quantitative fashion, in what became known as a General Geospace Circulation Model.

The structure of the GEM program was quickly mirrored by its meetings. Its annual June meeting consisted of two campaigns, convened sequentially, with modeling sessions overlapping the two campaigns in the middle of the week. The meetings encouraged international participation in the GEM program, student attendance participation and the vigorous integration of observation, modeling and theory. There has been a strong educational component with tutorials both for the specialist and students. Typically the participants began the day with discussions over breakfast, then gathered as a whole for tutorial lectures, retired into parallel splinter sessions during the day, and returned to some joint activity such as a poster session or a banquet in the evening. For many working groups in which rapid progress was being made, a second working group meeting was held in December on the afternoon prior to the fall annual meeting of the American Geophysical Union.

In the sections below we review the history of the program in two stages, its early history leading up to the funding of the first participants in 1991 and its first seven years from 1991 to 1997. Then follows a description of the first two campaigns: the Boundary Layer Campaign and the Magnetotail/Substorms Campaign, and the development of the General Geospace Circulation Model. Next we discuss the future growth of the program and its new campaign. The report closes with a discussion of the supporting ground-based program, its educational component and a bibliography summarizing the accomplishments achieved in the areas of the GEM campaign up to 1997.

2. HISTORY OF THE GEM PROGRAM

Between the initial study that led to the GEM program in 1987 and the awarding of the first GEM campaign in 1991, four planning workshops were held and summary reports issued. Since this was a very busy and formative period for the GEM program and since this is the first report setting down the history of GEM, it seems natural to divide the history of the GEM program into two chapters: a pre-campaign phase and a campaign phase. The first phase covers the period leading up to the awarding of the first GEM grants that enabled the first GEM campaign to begin and the second phase in which the work began. At this writing the third campaign has already begun but we will restrict our attention to just the first campaign and the first half of the second campaigns ending our discourse in 1997.

2.1 The Pre-Campaign Years - 1987 to 1991

"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)." These words by J. Roederer commenced the document that in May 1988 introduced and defined the GEM program: *Geospace Environment Modeling: A Program of Solar-Terrestrial Research in Global Geosciences – May 1988.* It is fitting to start this retrospective with Roederer's inspiring rhetoric, for two years earlier, in 1986, he initiated the process that led to the GEM program.

The year 1986 came shortly after the birth of the Global Change Program, which is a grandly envisioned plan conceived as a multi-disciplinary, multi-agency response to world-wide concerns over threats to the global environment from human activities, epitomized by depletion of the ozone layer and global warming. The administrators and scientists who formulated the Global Change Program thought big, billions of dollars big, which is a bigness commensurate with their perception of the seriousness of the threat. At that time, Congress shared their perception and made clear that it strongly endorsed and encouraged the program. With a firm congressional mandate, the Global Change Program became a juggernaut in the environmental sciences. Roederer, as Director of the Geophysical Institute of the University of Alaska sensed the need to involve solar-terrestrial research in this program and headed an effort to insert research supported under NSF's Solar-Terrestrial Program (which has since become the Upper Atmosphere Research Section) into NSF's part of the Global Change Program, the Global Geosciences Program.

In September 1986, Roederer and a group of scientists (Drs. S. Krimigis, L. Lanzerotti and G. Reid) met with NSF Director E. Bloch and Assistant Director W. Merell to propose, in Roederer's words, "that aspects of solar-terrestrial research relevant to the total Earth system be incorporated as integral components of the Global Geosciences Program of NSF." Out of the meeting, following a formal proposal, came a workshop funded through the Solar-Terrestrial Program, which was then headed by D. Peacock. The workshop was designed to spur new solar-terrestrial initiatives compatible with objectives of the Global Geosciences Program. The workshop convened on August 6, 1987 at the University of Washington in Seattle. For three days, 45 scientists debated the merits of various proposals looking for a project solar-terrestrially broad enough to embrace most of NSF's solar-terrestrial constituency yet terrestrially focused enough to qualify for legitimacy under the Global Geosciences Program. By this time, 1986, CEDAR had already been established and, with its manifestly atmospheric subject matter, had qualified for funding under the Global Geosciences Program. The challenge that the workshop faced, therefore, was to emulate the aeronomers' success with CEDAR with a program fashioned out of the remainder of the Solar-Terrestrial Program – the magnetosphere and the solar/heliosphere.

Two options emerged: 1. a program to determine the contribution that variations in solar irradiance make to climate change, and 2. a thorough program to study the general circulation of the magnetosphere. The first option, solar irradiance, had obvious relevance to the Global Change Program and was already listed among that program's projects, albeit with low priority. Though it won on relevance to the global-change juggernaut, in the end the irradiance option lost on relevance to the workshop, since it would engage professionally only a small fraction of the solar-terrestrial community. The second option, general circulation of the magnetosphere, touches nearly every aspect of magnetospheric physics; so it won on relevance to the solar-terrestrial community. It could affirm relevance to NSF's Global Geosciences Program by emphasizing the magnetosphere's terrestrial heritage as the fourth geosphere – lithosphere, hydrosphere, atmosphere, magnetosphere. Roederer, in the foreword to the May 1988 report describing the GEM program, implicitly defined the magnetosphere as a part of the Earth while leaving open a role for the solar/heliosphere community: "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...." The magnetospheric option also attempted to demonstrate relevance to the Global Change Program by making its central subject a magnetospheric analog of a subject that in meteorology provides a quantitative, mathematical approach to climate research – the general circulation of the atmosphere. Meteorologists' quest for a predictive understanding of the general circulation of the atmosphere had motivated them for decades to develop large computer codes – their "general circulation models" or GCMs – to numerically simulate global atmospheric dynamics. GEM adopted as its long-range goal the development of GCMs for the magnetosphere. In summary, the basic concept that emerged from the workshop was a community-wide program to systematically and comprehensively study the global dynamics of the magnetosphere that is responsible for the general circulation of the magnetosphere, which is a meteorological expression that magnetosphericists understood to mean magnetospheric convection, substorms, and storms. The success of the program was ultimately to be measured by its ability to encode the results of its studies in one or more magnetospheric GCMs, which the defining document of May 1988 designated MGCMs.

The defining document of May 1988 is remarkable because it laid out a detailed, systematic program that more than a decade later, with minor exceptions, is still being followed. The basic plan it prescribed was to parse geospace – it had already replaced "magnetosphere" with this more inclusive word – into natural, physically distinct regions and processes – magnetosheath, magnetopause and boundary layer, global magnetic field, magnetotail and substorm, convection and ionospheric coupling, and global plasma model. Then, over approximately a decade, subject each in turn to a nominally three-year campaign, with up to three campaigns running in parallel. Each campaign was to aim at reducing the characteristic features and processes of its domain to quantifiable laws understandable in terms of operative, domain-specific physics. Ideally, the results should be expressible in the form of a module in a modularized MGCM, that is, a black box that takes as inputs from adjacent modules values of a finite set of physical parameters and returns outputs in kind. So, when the whole suite of campaigns had been run and all the modules constructed from the information thus obtained, the modules could be assembled into a MGCM running in response to inputs from the solar wind with the ionosphere represented as a set of interactive, parameterized boundary conditions. Since the plan necessitated combining observations and theory, it introduced the idea of theory campaigns and observational campaigns running in parallel but interacting and together making up a campaign. It deserves to be noted that the idea of theory campaigns, which is a unique and highly fruitful innovation of the GEM program, originated with Chris Goertz, a key participant at the Seattle workshop and a member of the first GEM Steering Committee.

The program as envisioned in 1988 was financially ambitious by NSF standards. Each campaign was to be funded at between $500K to $1,000K annually, which for three campaigns running simultaneously adds up typically to between $2,500K and $3,000K annually. This was to be new money in the budget for magnetospheric physics coming from NSF's contribution to the Global Change Program. This money never materialized, however. Instead about $300K of new money from divisional resources was initially added to the magnetospheric budget to support all GEM activities – campaigns and workshops. Funding for GEM has slowly increased to about $500K.

Although the GEM program failed to become a major source of funds for magnetospheric research, the magnetospheric community quickly perceived that GEM offered something else of value. It provided a goal, a plan, and a forum for magnetospheric research. It gave a sense of direction and a way to measure progress. It gave an organizational structure that allowed the magnetospheric community to take on projects of greater scope than it could otherwise. It gave community coherence while maintaining community control. By featuring graduate student events (e.g., tutorials) and by promoting graduate student presentations, it gave a way for the community to "foster its young." As seen by the popularity of its summer workshops – over 200 attendees – and by the scientific productivity of the program, GEM has succeeded in making a qualitative difference in the amount, the coherence, the scope, and the purposefulness of magnetospheric research.

The defining document of 1988 laid out the GEM master plan that called for pre-campaign workshops to design campaign blueprints and to organize their implementation. In three busy years between 1988 and the inauguration of the first campaign in 1991, the GEM community organized and held three pre-campaign workshops and carried out one pilot program. The first pre-campaign workshops dealt with magnetopause and boundary layer physics. One was held on February 19 to 21, 1989 at the San Diego Supercomputer Center in La Jolla, California, with Maha Ashour-Abdalla the primary organizer. This workshop established the objectives and observational requirements of the Magnetopause/Boundary Layer Theory Campaign. The proceedings of this workshop were published in the *GEM Report on the Workshop on Magnetopause and Boundary Layer Physics (1989).*

A complementary pre-campaign workshop to establish the objectives and needed theoretical support for a corresponding Observational Campaign was held eight months later, October 29 to 31, 1989, at the University of Maryland at College Park with Ted Rosenberg, the primary organizer. The proceedings of this workshop were published in the *GEM Report of the Workshop on Ionospheric Signatures of Cusp, Magnetopause and Boundary Layer Processes.* This workshop addressed the challenging problem of inferring on the basis of observations made primarily from the ground – NSF's traditional purview – the nature, structure, and behavior of processes occurring at the magnetopause 100,000 km away. More specifically, its job was to devise a plan to identify and interpret such processes from their ionospheric signatures measurable from the ground. To test the basic premise of the plan – that such measurements are possible – it carried out a pilot campaign to intercalibrate ground-based photometer and radar data taken of a pre-selected targeted area of the ionosphere with data taken concurrently by overflying satellites.

The results of the pilot campaign, which successfully demonstrated proof of concept, were reported at the third of the mentioned pre-campaign workshops, which was held a year later at Northeastern University's Henderson House, Weston, Massachusetts, with Nancy Crooker the primary organizer. The proceedings of this workshop were published in the *GEM Workshop Report on Intercalibrating Cusp Signatures (1990).* Together the three workshop reports constitute a veritable compendium of information on the state of understanding around 1990 of cusp, magnetopause, and boundary layer structure and processes.

After three years of intensive preparation, the GEM program was now ready for its first real campaign.

2.2 The First Two GEM Campaigns

Despite its long gestation the GEM program did not appear strong and healthy when the first awardees were announced in the summer of 1991. Funds were limited and the awardees few in number. It was clear that the program would have to leverage existing programs to succeed. The first gathering of the nascent GEM community took place at UCLA on September 23-25, 1991 and gradually the form of the program took shape. An annual meeting was deemed essential. The resulting June meeting in Snowmass, Colorado has become the central pillar of the GEM effort. Table 1 lists the dates of these meetings. Some groups needed to meet more often. Generally the venue at these auxiliary meetings has been the day prior to the fall AGU meeting in San Francisco but occasionally other sites and dates have proven necessary.

Although the kickoff meeting at UCLA breathed life into the program, GEM did not take its first significant steps until its summer meeting in June 1992. The first three days of the meeting were devoted to the Boundary Layer Campaign and the second two days to forming a community consensus on the outstanding questions concerning the physics of the tail and substorms that stood in the way of the development of a General Geospace Circulation Model. This portion of the workshop produced a report entitled "Outstanding Questions in Geotail and Substorm Physics." The Boundary Layer Campaign organized its activities around the three working groups that are listed in Table 2. Reports from each of these working groups can be found later in this report. Working Group 1 on Boundary Magnetic and Electric Fields was initially chaired by O. de la Beaujardière and L. R. Lyons but, when de la Beaujardière accepted the job as NSF's director of the magnetospheric physics program, she stepped down as chair of WG1.

Table 1. The Summer Workshops

		Campaigns			
Year	Dates	1	2	3	GGCM
1992	June 29 - July 3	●	○	-	-
1993	June 28 - July 2	●	○	-	○
1994	June 27 - July 1	●	●	-	○
1995	June 26 - June 30	●	●	-	○
1996	June 24 - June 28	●	●	○	●
1997	June 16 - June 20	●	●	○	●
1998	June 15 - June 19	-	●	●	●
1999	June 21 - June 25	-	●	●	●

○ = Planning Activity
● = Campaign Underway

Table 2. Boundary Layer Campaign

WG	Topic	Conveners	Term
1	Boundary	O. de la Beaujardière	1992-1994
	Magnetic &	L. Lyons	1992-1997
	Electric Fields	N. Maynard	1994-1997
2	Particle Entry,	P. Newell	1992-1994
	Boundary	M. Ashour-Abdalla	1992-1993
	Structure	L. C. Lee	1993-1997
	& Transport	C. T. Russell	1994-1997
3	Current	R. Lysak	1992-1994
	Systems	C. T. Russell	1992-1994
	& Mapping	N. U. Crooker	1994-1997
		E. Friis-Christensen	1994-1997

Working Group 2 on Particle Entry, Boundary Structure and Transport was initially chaired by M. Ashour-Abdalla and P. T. Newell. Abdalla stepped down in 1993 to be replaced by L. C. Lee. Newell asked to be replaced in 1994 and C. T. Russell took his place. The third working group covered Current Systems and Mapping. Initially this working group was led by R. Lysak and C. T. Russell but when C. T.

Russell was asked to become chair of WG2 in 1994, N. U. Crooker and E. Friis-Christensen took the reins.

The Magnetotail/Substorms Campaign had one last planning session at the 1993 Snowmass meeting examining strategies for the Magnetotail/Substorms Campaign. The 1993 meeting was otherwise much the same in structure as the 1992 meeting but the General Geospace Circulation Model specification effort under G. L. Siscoe and J. A. Fedder was granted working group status and they held sessions overlaid on the other activities.

In 1994 the Snowmass meeting was divided essentially into three sections the Boundary Layer Campaign on the Monday and Tuesday, the General Geospace Circulation Modeling effort on Wednesday and the Magnetotail/Substorms effort on Thursday and Friday. This latter campaign like the Boundary Layer Campaign divided itself into three working groups as shown in Table 3. This structure lasted until 1997 at which time the Magnetotail/Substorms Campaign restructured itself. Reports on these activities are presented below.

Table 3. Magnetotail/Substorms Campaign

WG	Topic	Conveners	Term
1	Timing of Substorm Signatures	N. Maynard L. Lyons	1994-1997 1994-1997
2	Substorm Phenomenology, Observational Models	H. Spence T. Onsager	1994-1997 1994-1997
3	Quantitative Magnetotail Models	M. Hesse W. Lotko	1994-1997 1994-1997

The fabric of the GEM campaign and the essentials of the summer meeting remained unchanged through 1995 and 1996. In 1997 it was decided to wind down the Boundary Layer Campaign and transition to a new Inner Magnetosphere and Storms Campaign. This campaign met that year to begin to develop its strategy. In 1997 the original leaders of the GGCM Working Group retired and the GGCM effort was reformulated as a campaign under R. A. Wolf and M. Hesse and, following other campaigns, it divided itself into working groups: the spine under J. Raeder and F. Toffoletto; and the module under P. Pritchett and J. Birn. A brief overview of the plans of this campaign is given in section 5. The GGCM effort continued generally as before. Additionally this year, the Substorm Campaign restructured itself with L. R. Lyons assuming the helm as overall campaign convener with three working groups covering observations, quantitative models, and numerical models as listed in Table 4.

Table 4. Restructured Magnetotail/Substorms Campaign

WG	Topic	Conveners	Term
1	Observations	M. B. Moldwin S-I. Ohtani	1997-2000 1997-2000
2	Quantitative Tail & Substorm Models	J. Drake J. Lyon	1997-2000 1997-2000
3	Substorm Challenge	J. Raeder N. Maynard	1997-2000 1997-2000

The task of organizing the meetings and facilitating communication within the GEM community fell on the shoulders of the GEM coordinators who received small grants to support student travel to the meeting and the costs of organization. The initial meetings in 1991 and 1992 were organized by T. J. Rosenberg and C. T. Russell. In 1993 Ted Rosenberg took over the task of organizing the meetings and C. T. Russell concentrated on the newsletters and website. From 1995 to 1997 H. Spence took over the meeting organization while in 1998 J. Freeman took the reins.

Two major elements of the success of the GEM program are the leadership provided by the GEM steering committee and the support provided by the directors of the magnetospheric physics program at NSF. During the gestation phase G. L. Siscoe led the GEM Steering Committee. In 1991 W. Lotko took the helm to be replaced in 1994 by W. J. Hughes. In 1997 R. A. Wolf took over the reins. At NSF the program began with T. E. Eastman in charge of the magnetospheric physics program. Since this program is staffed by a rotator at NSF, he was soon replaced (1994) by Odile de la Beaujardière. She accepted a new position at NSF in 1996 and

R. M. Robinson took over as acting director. C. R. Clauer then was appointed to the directorship of the program only to be replaced in 1998 by K. B. Baker. The disadvantage of the rotating nature of the magnetospheric physics directorship is that it necessitated so many changes but its strength has been that it continually brought in individuals who were practicing scientists, not only familiar with GEM but also very dedicated to it.

3. FIRST CAMPAIGN: THE BOUNDARY LAYER

The Boundary Layer Campaign focused on the interface between the solar wind and the magnetosphere. It is across this region that all energy from the solar wind must flow. At low latitudes the magnetopause current layer is a clear demarcation point for the study of the region separating the boundary region into external and internal layers. Figure 1 shows the magnetopause current layer and a cutaway look at the interior of the magnetosphere. While the solar wind pressure shapes the magnetosphere, the stresses on the magnetosphere due in part to the interplanetary magnetic field do the work on the magnetosphere that causes the plasma to circulate. Field-aligned currents couple the outer magnetosphere to the low latitude regions. Based on this paradigm it was natural to divide the Boundary Layer Campaign into three working groups: Reconnection Electric Field and Magnetopause Boundary Normal Magnetic Field; Particle Entry, Boundary Layer Structure and Mapping; and Current Systems and Mapping. The first of these covers the driving magnetic and electric fields and the resulting convection of the plasma. The second covers the entry of mass into the magnetosphere and the third how the stress is transmitted to the ionosphere from the magnetosphere. Reports on the activity of these three working groups follow.

3.1 Reconnection Electric Field and Magnetopause Boundary Magnetic Field

Introduction

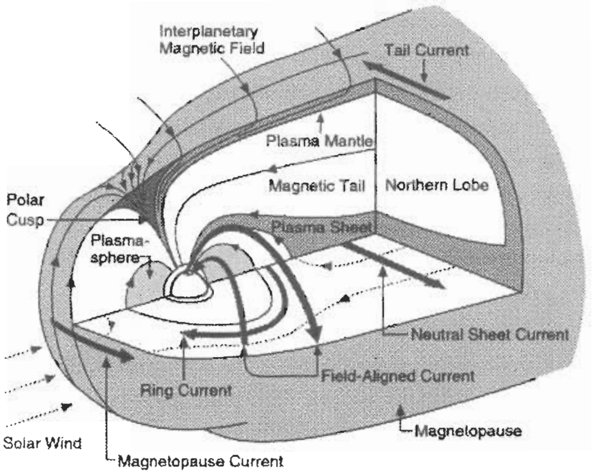

Fig. 1. The configuration of the magnetosphere showing the overall shape of the magnetopause as governed by the solar wind dynamic pressure and the interplanetary magnetic field. The principal regions of the magnetosphere are shown and a cutaway indicates how the stresses in the outer magnetosphere are linked to the ionosphere by field-aligned currents.

Activities of this working group focused on improving the understanding of the reconnection electric field and the normal component of magnetic field B across the magnetopause. The normal component of B gives a mapping of the interplanetary electric field to the magnetosphere and the distribution of the normal component of B over the magnetopause surface determines the direction and magnitude of the convection electric field throughout the open-field-line portion of the magnetosphere. The convection electric field extends across the magnetic separatrix (the boundary between open and closed magnetic field lines) to the closed-field line region of the magnetosphere. At the separatrix, the convection electric field is associated with the transfer of magnetic flux, plasma, and energy to and from the closed field lines region, and the electric field at the separatrix, in the frame of reference of the separatrix, is referred to as the reconnection electric field. The convection electric field maps along magnetic field lines to the ionosphere, where it can be measured via the two-dimensional patterns of ionospheric convection. Since magnetic field-aligned potential drops are not large (generally $\lesssim 1$ keV and essentially always $\lesssim 10$ keV) within the region of open polar-cap field lines and at the separatrix, ionospheric electric potentials give a good measure of the potential distribution throughout the open-field-line region of the magnetosphere. Also, measurements of ionospheric convection give measurements of the reconnection electric field, provided the mapping of the separatrix to the ionosphere can be identified.

This working group has emphasized coordinated observational studies of the polar-cap ionosphere using data from low-altitude polar orbiting satellites and a large number of ground instruments. This entailed working with a large number of researchers from various institutions throughout the national and international scientific community. By doing this, we have been able to leverage resources that have been made available for a variety of national and international projects as well as for GEM, and we have been able to use extensive, coordinated data sets from diverse sources. Projects have included the development of techniques for identifying the magnetic separatrix, evaluating flow across and in the vicinity of the separatrix, and evaluating flow patterns throughout the polar caps and their relation to the separatrix and boundary layers, the dependence the flow patterns on the interplanetary magnetic field (IMF), and flow pattern evolution in response to IMF changes.

Flow Across and in the Vicinity of Dayside Separatrix

In order to use ionospheric observations to measure the reconnection rate and to accurately determine flow patterns within the polar-cap region of open magnetic field lines, it is necessary to identify the separatrix as mapped to the ionosphere. In addition to using precipitating particle data from polar-orbiting satellites, three different approaches for identifying the separatrix in the vicinity of the dayside cusp have been evaluated and found to be useful. One technique uses photometer data, which can be taken in darkness near the cusp from Svalbard during January. G. McHarg, J. Minow and R. Smith showed that the cusp and its equatorward boundary can be identified using a combination of 5577 and 6300 Å emission measurements. With these wavelengths the average energy of precipitating particles can be obtained, and the cusp shows up as a distinct region of low average energies and enhanced 6300 Å emissions. A best estimate of the location of the separatrix was found to be ~ 60 km equatorward of the low-latitude boundary of the cusp identified from 6300 Å emissions.

The other two techniques for identifying the separatrix employ the same radars that are used to measure the flow. These are based on electron densities and temperature measured with incoherent scatter radars [Watermann et al., 1994] and on the equatorward edge of the cusp as determined from the returned signals of HF coherent scatter radars which have large spectral widths within the cusp [Baker et al., 1995]. The relationship between the optical and HF radar identifications was addressed by Rodger et al. [1995], Rodger and Pinnock [1997] and Rodger [1998], and these identification were found to agree to within ~100 km. The HF radars measure in two-dimensions, allowing the orientation of the separatrix to be determined, and Baker et al. [1997] found that the orientation correlated well with the IMF By. They were also able to determine the total potential drop within the field-of-view of the radar and found that it varies from the majority of the total cross-polar-cap potential drop to about half of the total potential drop. G. T. Blanchard has recently found that the separatrix near noon can be identified quite accurately with incoherent scatter radar measurements of E-region ionization after corrections are made for photoionization, the separatrix being quite well identified by the poleward edge of E-region enhancements. These identifications are now being combined with radar flow measurements to statistically evaluate the dayside reconnection rate as a function of MLT and the IMF.

Variations in ionospheric currents and densities near the dayside separatrix have been found to be directly related to variations of the IMF. Stauning et al. [1994] and Stauning [1994] used ground-based measurements from Greenland to evaluate ionospheric currents in the region poleward of the dayside separatrix. They found a dramatic association between oscillations in the IMF By component and the ground magnetic H-component (which is a measure of ionospheric currents) in the region of the cusp (see example in Figure 2). These results show a direct connection between the interplanetary electric field and the polar-cap electric fields that drive the ionospheric currents. The oscillations were found to propagate poleward across the polar cap from the magnetic separatrix and were termed "poleward progressions." The poleward motion appears to result from the motion of the IMF oscillations as they are carried across the magnetosphere by the solar wind. These events are found only for IMF Bz < 0 and have a maximum occurrence rate near noon. Similar H-component perturbations are also found when the IMF Bz > 0, but the perturbations do not propagate poleward. Relations between the ionospheric Hall current and convection during these events were considered by Clauer et al. [1995], and Papitashvili et al. [1995] compared the potential patterns during these events to statistical potential patterns inferred from ground magnetometer data. Rodger et al. [1994] found that variations in reconnection and flow in the vicinity of the dayside separatrix also affect the formation and flow of patches of enhanced F-region ionization that propagate from near the dayside separatrix and propagate across the polar cap. However, despite the existence of significant variations in the rate of dayside reconnection as a function of time and position along the separatrix, reconnection has been inferred to be a continuous process that extends along the entire dayside portion of the separatrix [Maynard et al, 1997].

Lu et al [1995a] studied convection and field-aligned currents near the dayside separatrix and found that the separatrix was located a few degrees in latitude equatorward of the maximum in dayside convection that is sometimes referred to as the convection “throat”. They also found regions of sunward flow within the equatorward portion of the cusp that cannot be explained by the curvature of flow that is associated with the y-component of the IMF and that field-aligned currents associated with the cusp and mantle are on open field lines as expected if they are indeed in the region of cusp/mantle particle precipitation.

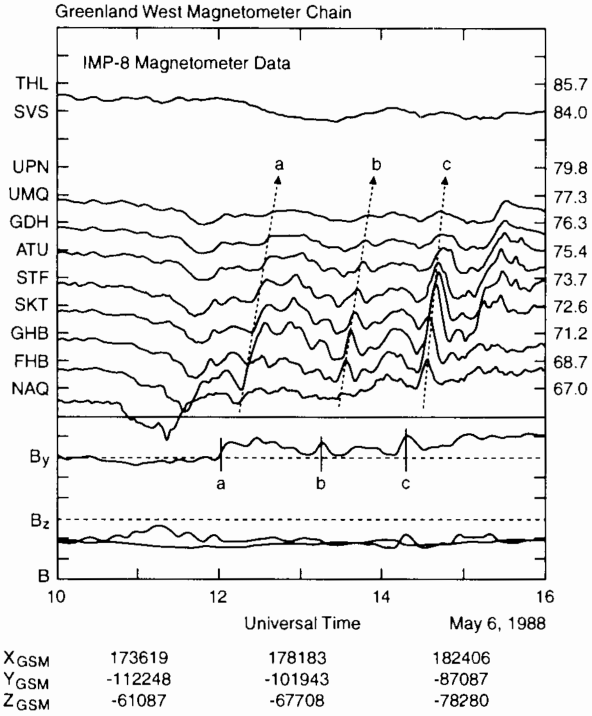

Fig. 2. *Example of poleward progressing events in the geomagnetic H-component s recorded at the Greenland West Coast chain of magnetometers for 10-16 UT on May 5, 1988. IMF data from IMP-8 is also shown (from Stauning et al. [1994]).*

Incoherent-Scatter Radar Measurements of Nightside Reconnection

Measurements of plasma flow across the nightside separatrix require identification of this boundary in the nightside ionosphere. This boundary is generally believed to coincide with an abrupt transition from soft polar-rain electron precipitation to the much stronger and harder electron precipitation associated with the plasma sheet on closed magnetic field lines. Plasma sheet precipitation causes enhanced auroral emissions that can be measured with ground-based photometers and enhanced electron densities that can be measured with ground incoherent-scatter radars. The study began by examining auroral emissions near the separatrix in three wavelengths, 6300 Å, 5577 Å, and 4861 Å [Blanchard et al., 1995, 1997a]. The meridional structure of these emission lines was compared to the meridional structure of the precipitating particle energy spectra measured by the DMSP F9 satellite in close proximity to the ground station making the auroral emission measurements. It was shown that the signature of the separatrix is most prominent in the 6300 Å emission. By parameterizing the 6300 Å emission intensity with a latitudinal step function, it was found to be possible to determine the latitude of the separatrix within 1.0° of latitude, which approximately equals the latitudinal resolution of the measurements.

The consistency between using 6300 Å emissions to identify the separatrix and the separatrix inferred from radar measurements of a decrease in ionospheric E region electron density to below a specific level [de la Beaujardière et al., 1991] was then investigated. The 6300 Å emissions were measured at Sondrestrom in the same meridian, as was the ionospheric electron density with the Sondrestrom incoherent scatter radar. It was found that the latitude of the separatrix identified by these two independent methods agrees to within 0.6° [Blanchard et al., 1996].

Once the ability to locate the separatrix was developed, the Sondrestrom Incoherent Scatter Radar was used to measure ionospheric plasma flow through the separatrix to determine the reconnection rate [Blanchard et al., 1996]. It was found that reconnection occurs at all magnetic local times on the nightside; however, the reconnection rate is largest near magnetic midnight. The average reconnection rate as a function of MLT (see Figure 3) is well fit by a cosine-squared function shifted by 0.5 h toward dusk. It was also found that the nightside reconnection rate responds to the southward-rectified interplanetary magnetic field (IMF) with a delay of 72 min, which is the characteristic ionospheric convection time across the polar cap. Substorms were also found to have an effect on the nightside reconnection [Blanchard et al., 1997b].

Flow Patterns within the Polar Caps and Effects of IMF Changes

Extensive use has been made of the assimilative mapping of the ionospheric electrodynamics (AMIE) procedure [Richmond, 1992]. This procedure uses a least-squares fit of coefficients to observed data; each observation being weighted by the inverse square of its effective error. For GEM studies, large data sets were obtaining data from polar magnetometer stations, several coherent and incoherent scatter radars, and low-altitude, polar-orbiting DMSP spacecraft.

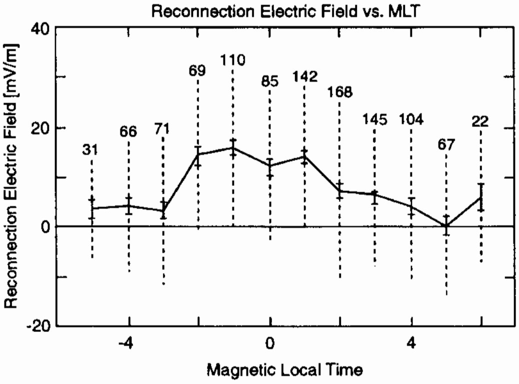

Fig. 3. Average reconnection electric field as mapped to the ionosphere in 1-hr bins for all levels of geomagnetic activity versus MLT. The numbers above each error bar give the number of measurements in each bin. Dashed error bars give the standard deviation of the measurements in each bin. Solid error bars give the standard error of the mean in each bin. (from Blanchard et al. [1996]).

Knipp et al. [1993] used AMIE to study the changes in convection over both polar caps during a period of large, but slow, IMF variation in a northward field and found important new results. They found that the reversed convection, (dusk-to-dawn electric fields near the center of the polar cap) that is associated with northward IMF, occurs when the IMF $B_Z > |B_y|$; whereas dawn-to-dusk electric fields across the polar caps were maintained when $|B_y| > B_Z$, even for $B_Z > 0$. They also found that large values of $|B_y|$ lead to large cross-polar-cap potential drops of 80-100 keV for $B_Z > 0$, demonstrating that B_y is important in determining the strength of convection. Additionally, significant differences in the simultaneous convection in the two polar-caps were observed when the IMF was strongly positive. While such differences had been inferred before from measurements of individual polar caps, this was the first time such differences were directly verified from simultaneous observations of both polar caps.

Differences in convection between the polar caps was found to extend to positive IMF B_z periods with $B_y| > B_z$ by Lu et al. [1994]. Specifically, they found significantly larger cross-polar cap potential differences in the southern hemisphere than in the northern hemisphere during a GEM campaign period of January 27-19, 1992.

Lu et al. [1995] used AMIE outputs for a GEM campaign period of March 28-29, 1992 as inputs to the NCAR thermosphere-ionosphere general circulation in order to evaluate effects of coupling between ionospheric convection and electrodynamics and thermospheric dynamics. They found that magnetospheric electrodynamic energy goes mostly to Joule heating of the thermosphere, with only a small amount (6%) going to acceleration of thermospheric winds. However, they also found that the thermospheric winds can cause an ~25% reduction in Joule

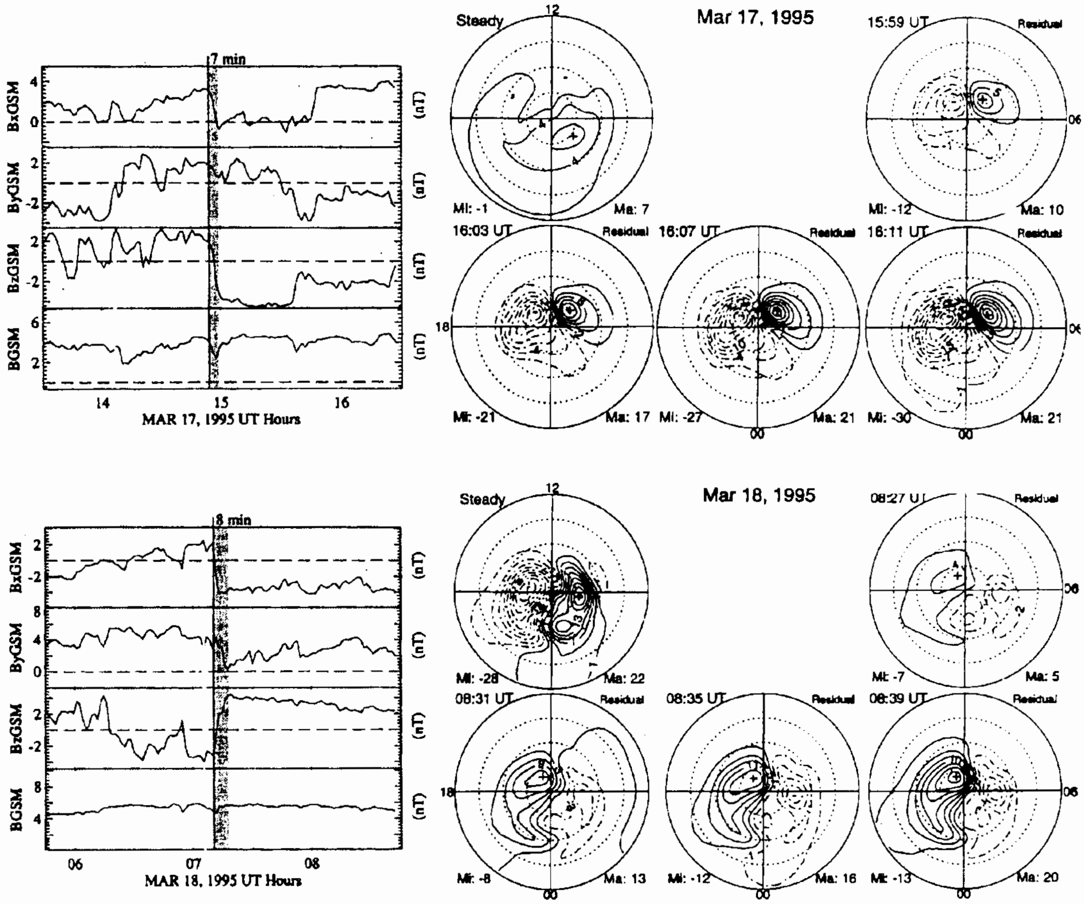

Fig. 4. IMF from the WIND spacecraft showing southward (top left panels) and northward (bottom left panels) turnings on March 17 and 18, 1995, respectively, and convection responses based on AMIE. Potential patterns labeled "Steady" show average patterns during the several minute periods of relatively steady convection prior to the effects of the IMF turnings, which are estimated to have contacted the magnetopause at 1554 UT on March 17 and 0820 UT on March 18. Patterns labeled "Residual" are the AMIE patterns for the indicated UT's after subtraction of the preceding steady pattern. (based on Ridley et al. [1998]).

heating and in field-aligned currents that connect the magnetosphere to the ionosphere. These results suggest that while only a small fraction of magnetospheric energy goes to neutral wind acceleration, the neutral winds have significant effects on magnetosphere-ionosphere coupling. Ridley et al. [1998] examined AMIE potential patterns for 65 well-defined IMF changes, such as the negative to positive and positive to negative changes shown in Figure 4. For each case, they first evaluated the convection pattern for the period of steady positive or negative IMF that preceded the IMF change. The panels labeled "steady" in Figure 4 show the strong steady convection pattern that existed before the northward turning of the IMF that occurred soon after 07 UT on March 18, 1995 and the very weak convection that existed before the southward turning of the IMF that occurred just prior to 15 UT on March 17, 1995. Ridley et al. then subtracted the "steady" pattern from ensuing patterns and examined the differences, which they referred to as "residuals". This novel approach very dramatically revealed how IMF changes effect magnetospheric convection. As seen by the residuals in Figure 4, the responses to northward and southward changes in the IMF are essentially the same, except for the sign of the change in potential. The changes are very rapid, the average time to initiation of a convection change being ~10 min after the causative IMF change is estimated to have contacted the dayside magnetosphere for both northward and southward turnings. Ridley et al. found that the entire polar cap responds together, and that the average time for full reconfiguration of polar cap convection is ~12 min which is only slightly longer than the time scales of IMF turnings. These new results should have important consequences on our understanding of how the electric field carried by the solar wind is transmitted to the magnetosphere. However, these results need to be reconciled with the findings of Blanchard et al. [1996] that the nightside reconnection rate responds to the southward-rectified interplanetary magnetic field (IMF) with a delay of 72 min. Such reconciliation would be expected to be related to the poleward and equatorward motions of the nightside separatrix. This issue is an important topic for the new M/I/C working group.

The GEM Grand Challenge

As a result of the successes of the GEM data analysis studies and the maturity of magnetospheric modeling techniques, it was decided to use the GEM results to pursue rigorous test of global models. One of the projects pursued by WG1 of the Boundary Layer Campaign was a construction of synoptic maps of convective flows and particle regions within the polar ionosphere for different orientations of the IMF [Lyons et al., 1996]. In 1996, the GEM steering committee recommended that these synoptic maps be used for model-data comparisons to provide tests of model convection patterns, convection strengths, separatrix locations, boundary layers, and currents. The requested model-data comparison was viewed as a challenge from the data analysis community to the modeling community and became known as the "Grand Challenge" [Lyons, 1998]. This challenge lead to set of model-data comparison papers that are being published together in the Journal of Geophysical Research, and these papers represent a major highlight of GEM-motivated collaborations involving the international scientific community and both modeling and data analysis studies.

It was decided to use observations from the GEM interval of 27-29 January 1992, when four polar-orbiting DMSP satellites were in operation. The DMSP satellites measure both electric fields and particle precipitation, so that use of data from this period allowed more observational coverage of the polar caps than is normally available. Periods of relatively steady interplanetary magnetic field (IMF) were then identified and data were used from multiple satellite passes during each period to obtain unprecedented two-dimensional coverage. Four periods of relatively steady IMF were selected. Two had large negative B_Y and moderately large negative B_Z, one having larger $|B_Y|$ than the other. The third interval had IMF conditions very similar to the previous two intervals except for the crucial difference that B_Z was positive. This interval allowed us to consider directly the effects of the sign of B_Z. The final interval, had small $|B_Y|$ and $B_Z > |B_Y|$. This interval gave information on the northward-directed IMF conditions that lead to sunward flow near the center of the polar cap.

Synoptic Space Weather Maps

Figure 5 shows maps of both polar caps for the interval 01:15 UT +/- 170 minutes on 28 January. Particle and electric field data were used from every DMSP pass during the interval, the passes over the polar caps being indicated by light-dashed lines in Figure 5. The heavy solid curves in Figure 5 gives the location of the separatrix determined from the observed boundaries between the plasma sheet and either polar rain or the cusp. The spatial extent of the region near noon where cusp/mantle ions were detected is indicated in the figure. Since the cusp and mantle form one continuous region of ions extending from the dayside separatrix, no attempt was made to separate the cusp from the mantle. For this case, the open field line region was approximately circular and centered near the magnetic pole.

Ionospheric electric equipotentials obtained from AMIE are also shown in Figure 5. The distributions of height-integrated horizontal ionospheric and field-aligned currents were also available from this fitting procedure. The equipotential contours show the overall pattern expected for large negative IMF B_y conditions. In the southern hemisphere, a circular convection cell is centered in the afternoon sector and extends across the noon-midnight meridian, and a "crescent-shaped" cell is centered near 06 MLT. In the northern hemisphere, a crescent-shaped cell appears on the dusk side. However, the dawn cell is far less circular than is the dusk cell in the southern hemisphere. This interhemispherical asymmetry is consistent with previous observations. The equipotentials in Figure 5 cross the separatrix at all local times. This indicates that, when averaged over the time interval, reconnection occurred at all, or nearly all, local times, and that the average reconnection rate varied smoothly as a function of local time.

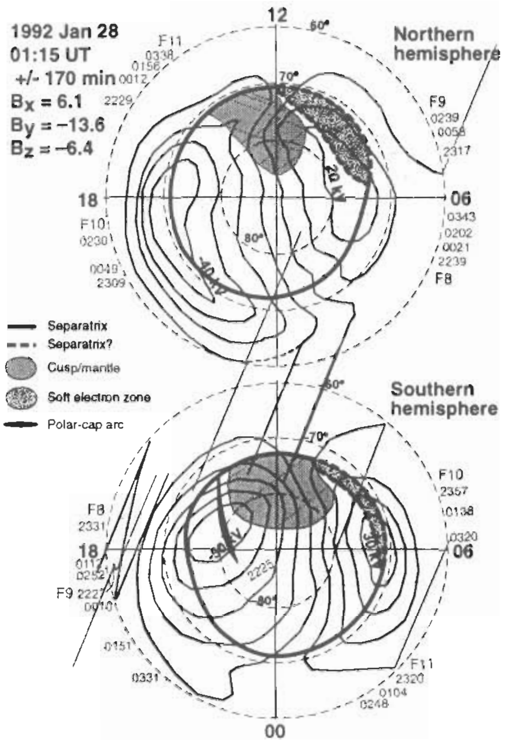

Fig. 5. Synoptic space weather maps of the polar caps for the time interval 01:15 UT +/- 170 min on 28 January obtained by drawing smooth curves through the various boundaries obtained from the indicated passes of the DMSP spacecraft during the interval. Light dashed lines give the trajectories of all the DMSP passes within the interval, each trajectory identified by the DMSP satellite number and the UT at which it moved poleward across 60° latitude. DMSP F10 was within the southern polar cap at the beginning of this time interval (2225 UT), so that its location at 2225 UT is indicated. Solid curves give equipotential contours at 10 kV intervals obtained from AMIE for this interval. B_x, B_y, and B_z are the IMF components at the center time of the interval. [Lyons et al., 1996].

In Figure 5 a specific precipitation feature is identified in the pre-noon sector as a "soft-electron zone" (SEZ). SEZ precipitation lies between the plasma sheet and the region of polar rain. It is readily identifiable by a discontinuous decrease in ≥ 1 keV plasma sheet electrons that is essentially the same as that observed at the equatorward boundary of the cusp and it contains pronounced spatial or temporal structure [Burch, 1968]. The SEZ shown here excludes the cusp and mantle, which are identified separately, but includes the low-latitude boundary layer (LLBL) and dayside boundary plasma sheet (BPS). Analysis of the data from this GEM period suggests that, with the cusp and mantle excluded, the SEZ is a continuous region lying between the plasma sheet and polar rain Thus, it appears to not be appropriate to separate the SEZ into LLBL and BPS portions. The SEZ can appear at both afternoon and morning local times and can extend onto the nightside. Whether or not the SEZ is entirely on open field lines has yet to be definitively determined. The heavy dashed line in Figure 5 indicates this uncertainty showing the separatrix possibly lying on either side of the SEZ. However, significant evidence exists that the SEZ is at least partially on open field lines.

The larger $|B_Y|$ case showed potential patterns and relative locations of boundaries regions very similar to those for the previous case. However, for this larger $|B_Y|$ situation, the potential patterns within the circular cell are more circular, particularly in the northern hemisphere. The resulting difference in the flow directs mantle plasma far more towards the afternoon side in the northern hemisphere and towards the morning side in the southern hemisphere. A shift of the region of open field lines towards dusk in the northern hemisphere and towards dawn in the southern hemisphere was found to be more pronounced than for the previous case.

The AMIE potential patterns for the case of large $|B_Y|$ but positive B_Z showed that circulation is confined to higher latitudes for positive B_Z than for negative B_Z, and that the potential drop across the polar cap is significantly lower in the northern hemisphere only. The difference in the potential drops across the polar caps obtained by AMIE was 30 keV for this positive B_Z interval, and similarly large differences were found by Lu et al. [1994] from instantaneous AMIE patterns during this interval. Significantly less equipotentials cross the separatrix for this positive B_Z interval than for the negative B_Z intervals, implying a significant reduction in the average reconnection electric field. As compared to the negative B_Z cases, the positive B_Z case showed a several degree poleward displacement of the dayside separatrix but little change in the location of the nightside separatrix. We also obtained a significantly increased polar-cap displacement toward the dusk in the northern hemisphere and towards the dawn in the southern hemisphere as compared to the negative B_Z cases. The cusp/mantle region was not strongly affected by the sign of B_Z.

During the interval with $B_Z \gg |B_Y|$, strong (~500-1000 m/s) sunward flow was observed in the northern hemisphere in the 06-12 MLT region at latitudes above 85° and a well-defined relation between flows and boundary layers over the northern polar-cap was found. The overall pattern is quite symmetric with respect to the noon-midnight meridian plane. In the polar cap region of polar rain, sunward flow is observed on the high-latitude dayside passes, whereas anti-sunward flow was observed on the passes that crossed the polar cap between 72° and 75° latitude within a few hours of midnight.

Model Comparisons with Synoptic Maps

Five different models were run for the intervals of relatively stable IMF described above and the model potential patterns and separatrices were compared with the respective synoptic map. Each of the models was found to have individual strengths and weakness, and areas where the models comparisons will facilitate model improvements were identified.

Model data comparisons were particularly illuminating for the "Rice open magnetosphere model", which has the primary purpose of calculating polar-cap potential patterns as a function of the IMF using a prescribed magnetopause shape and physics-based prescription for the magnetosheath flow and for the distribution of the magnetic-field component normal to the magnetopause [Hill and Toffoletto, 1998]. It was found that the model reproduced the observed shape of the convection patterns very well. However, the model was found to give regions of open polar-cap field lines that are smaller than observed. This discrepancy was found to increase for increasingly northward IMF. This evaluation of the model's error in locating the separatrix helped identify planned changes to the model that ought to significantly improve the model's ability to evaluate the location of the separatrix.

Comparisons were also useful for the source surface model [Peroomian et al., 1998], which is also a prescribed magnetopause model with a specified distribution of the magnetic-field component normal to the magnetopause. This model is particularly useful for studying the effects of field-aligned currents, since they can be added to the model with specific distributions. The model was found to do a reasonably good job of reproducing the polar-cap flow patterns. It also reproduced the location of the nightside separatrix quite well, though the strongly northward IMF case was not considered. The model, however, calculated a dayside separatrix that was a few degrees in latitude too far poleward. Incorporation of field-aligned currents reduced, but did not remove, this discrepancy. This current incorporation did, however, demonstrate that field-aligned currents can have significant effects on the location of the separatrix. The model was also used to show that a 9-14% penetration of the IMF across the magnetopause can account for the observed cross-polar cap potential drops

Results from two MHD models were compared with the synoptic maps [Raeder et al., 1998; Fedder et al., 1998]. Both models were found to reproduce the ionospheric potential patterns quite well. However, both models obtained cross-polar cap potential drops that were approximately a factor of two larger than was observed, which lead to important considerations of what in models may lead to this discrepancy. Understanding of the causes of this discrepancy could lead to important advances in our quantitative understanding of how the interplanetary electric field is imparted to the magnetosphere. It was interesting to find that the two models obtained quite different locations for the magnetic separatrix. The separatrix in the Raeder et al. model agreed quite well with the observations, though on the dayside the model separatrix was a few degrees too far equatorward. The separatrix obtained from the Fedder et al. model was about as accurate as from the Raeder et al. model on the dayside, but was at much too high a latitude (~10° too high) on the nightside. It is currently not know why the two MHD models obtained such different results for the location of the nightside separatrix; however understanding of this difference could yield valuable information on what are the important factors in determining the separatrix location.

A fifth comparison used both an MHD-based model and statistical potential patterns obtained from ground-based magnetometers and low altitude satellites [Winglee et al., 1997]. As with the MHD models, this model predicted cross-polar cap potential drops about a factor of two larger than observed. Separatrix locations had about the same accuracy as obtained with the Raeder et al. model, but the modeled potential patterns agreed less well with the observations than did the other models.

Summary

WG1 made significant progress toward accomplishing the goals of the GEM Boundary Layer Campaign. Techniques for remotely identifying the separatrix using ground-based measurements have been developed for the dayside and nightside and have been applied to obtain important results on how reconnection varies with MLT and the IMF. It was found that convection throughout the polar-cap region of open field lines responds quickly and directly to IMF variations. This critical dynamic feature of the magnetosphere needs to be understood properly to model the magnetospheric response to its solar wind energy source. Important new information has also been found on the effects of the IMF y- and z-components on magnetospheric convection, on the relation of dayside field-aligned currents and polar cap convection to the separatrix and polar cap boundary layers, and on energy input to the thermosphere.

The GEM Boundary Layer Campaign has now been completed and WG1's activities are finished. One of the major accomplishments has been a greatly increased cooperation between ground-based and satellite observers on an international level. The collaborative approach used by WG1 for the assimilation of a large-amount of data from ground-based and low-altitude satellite instrumentation is being carried over to the newly formed Magnetosphere-

Ionosphere Coupling Working Group with the goal of obtaining results that are of importance to broader-scale magnetospheric problems and to the ongoing GEM Magnetotail/Substorms and Inner-Magnetosphere Working Groups. GEM successes have also helped to stimulate enhancements of ground-based observing networks within both the U.S. and international communities. This will have a positive impact on research well into the future. The Grand Challenge comparison of large-scale observational results with a number of models has been highly illuminating, illustrating many of the benefits and limitations of current models. It has also had great value by enhancing the cooperation between modelers and experimentalists. This approach is being carried forward in GEM to the Magnetotail/Substorms Campaign by the identification of a limited number of well-defined events and time periods that have extensive ground and satellite data coverage. This will provide large-scale observational bases for testing of models and theories for magnetotail and substorm dynamics.

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3.2 Particle Entry, Boundary Layer Structure and Transport

The first campaign of the GEM program was devoted to understanding the coupling between the solar wind and the magnetosphere as manifested at the magnetopause, in the boundary layers surrounding the magnetopause and in the polar cusp. To address this problem in situ observations both at high altitudes and low altitudes, ground based measurements with radars, photometers magnetometers and riometers as well as simulations and theory were brought to bear. Much was learned in the campaign. The relative roles of reconnection and diffusion in forming the boundary layers was explored. An appreciation that there was an exterior boundary layer outside the magnetopause current layer as well as inside was developed. The role of pressure pulses and transient reconnection on the magnetopause was examined as was the role of the foreshock in causing each. The dispersion signatures in cusp plasma was interpreted in terms of reconnection with the solar wind and various transient phenomena in the magnetosphere were identified with both pressure and reconnection transients. In the paragraphs below we expand upon these topics.

Magnetospheric Transients

The outer regions of the magnetosphere are visited by numerous compressional disturbances. Various postulates have been made for such disturbances from pressure pulses in the solar wind, to pressure modulations due to the foreshock and its variations to transient reconnection. While this topic was the subject of much debate over the last several years, we now recognize that there are two distinct types of transients in the outer magnetosphere. Pressure fluctuations produce large-scale variations that reach far into the magnetosphere. Transient reconnection produces smaller scale fluctuations that are largest at the magnetopause and that decay in amplitude with distance from the magnetopause. These phenomena co-exist and are usually distinguishable.

Dayside Low-Latitude Boundary Layer

Prior to the GEM Boundary Layer Campaign the paradigm for the formation of the low-latitude boundary layer was that when the IMF was northward, cross-field diffusion and momentum-transfer-associated, wave-induced boundary motions produced the boundary layer. When the IMF was southward, plasma entered the magnetosphere through reconnection. However, the BL Campaign clearly demonstrated that reconnection plays a critical role for both northward and southward IMF conditions with high latitude entry for strongly northward IMF. Cross-field diffusion and wave processes play at most a minimal role in the entry of plasma in the dayside boundary layer, although they may modify the plasma within this region. Most of the dayside LLBL is now believed to be on open field lines for southward IMF.

Inner Magnetosheath Boundary Layer

Just as a boundary layer forms on the inside of the magnetopause, another forms on the outside of the magnetopause, between it and the magnetosheath flow. This boundary layer was discovered well before the advent of the GEM campaign and described in terms of the depletion of magnetic flux tubes by a combination of kicking (at the shock) and squeezing the particles along the magnetic field away from the subsolar region. One of the successes of the Boundary Layer Campaign was the recasting of this theory in terms of the MHD solution of the interaction of a flow with an obstacle; thus, this layer is now recognized to consist of a slow mode compression of the plasma followed by a slow mode rarefaction as the plasma expands as it flows around the obstacle. When the magnetopause is a reconnecting boundary, however, this slow mode structure does not develop as such. Rather any slow mode structure is enveloped in the structure associated with the magnetopause itself.

Dayside Auroral Forms Associated with Transient Reconnection

As the GEM program began interest was strong in identifying the dayside auroral manifestation of transient reconnection on the magnetopause. Early attention focused on twin convection vortices but these phenomena did not seem to exhibit the intimate control by the IMF associated with reconnection induced phenomena. Rather poleward moving auroral forms (PMAFs) seemed to be the low altitude manifestation of high altitude reconnection. As illustrated in Figure 6, these auroral features move poleward out of the dayside oval with a temporal spacing very similar to that of flux transfer events. Like FTEs they occur predominantly for southward IMF conditions. Nevertheless some controversy still exists on the source of both PMAFs and TCVs, and work still needs to be done in this area.

Cross-Scale Coupling at the Magnetopause

The role of microprocesses is a major unresolved problem for the dayside magnetopause. With the lack of a well-identified dissipation mechanism, macroscale modelers often assume resistivity to provide the necessary dissipation for reconnection. The majority in the community assume that whatever dissipation is required by the magnetic reconnection will ultimately be provided, say by the thinning of current sheets until the current can no longer be carried. Nevertheless an intrepid few have persisted in determining how this dissipation is provided using theoretical techniques, numerical simulations and observations. The working group has fostered and encouraged such efforts but there is still much to be done in this area.

Flux Transfer Events

When the interplanetary field is southward, a very particular disturbance of the magnetopause is found in which the magnetic field has an outward then inward-pointing magnetic field or vice versa for about 30s. This repeats about every eight minutes. While these disturbances cause the magnetopause to move, they are not simply due to a motion of the magnetopause. Rather they appear to be a bundle of magnetic flux that has become reconnected as illustrated in Figure 7. Examination of the plasma and field data clearly reveal a core in which magnetosheath and magnetospheric plasma are mixed and a draped field region of either magnetospheric plasma or magnetosheath plasma in which the magnetic field has clearly been bent or draped around the elongated tube. Flux transfer events occur over the entire magnetopause and are not correlated with the location of the upstream waves or quasi-parallel shock.

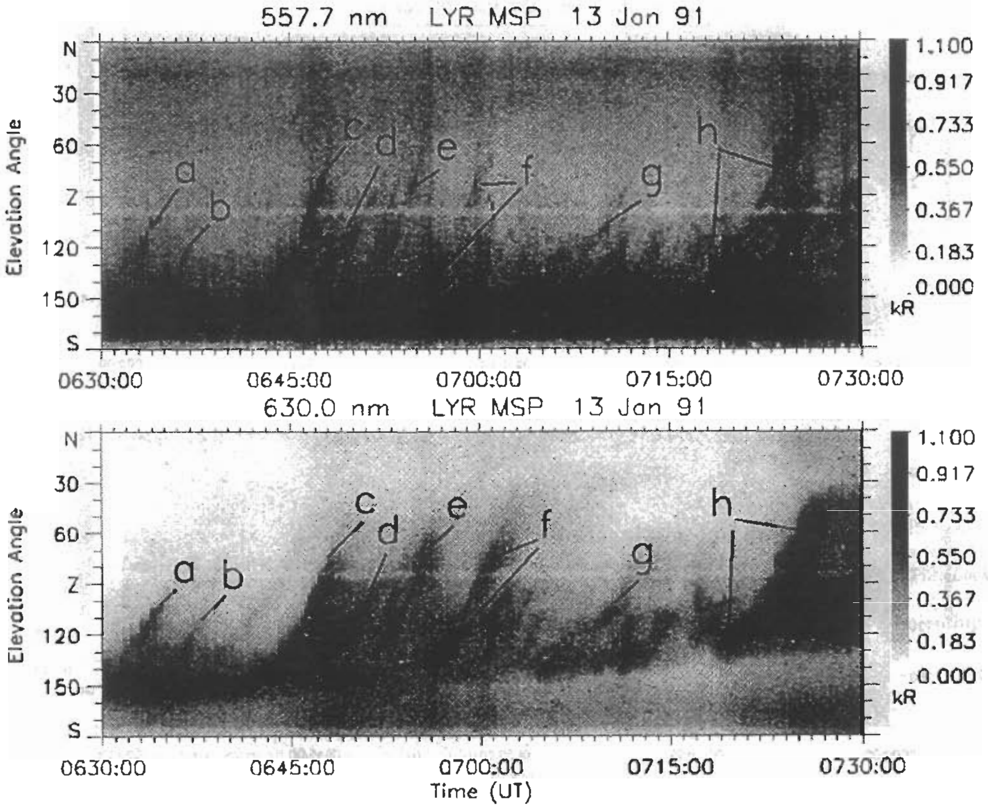

Fig. 6. Grayscale plot of the intensity of 577.7 nm and 630.0 nm emissions on January 13, 1991 as a function of elevation angle along the magnetic meridian at Svalbord. Poleward moving auroral forms are the long dark structures, slanted toward increasing time and labeled a to h.

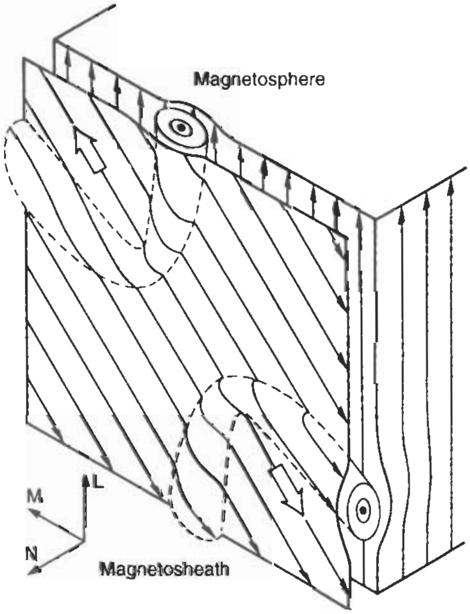

Fig. 7. Artist's conception of a flux transfer event (FTE). Reconnection has just occurred for a limited period of time forming two regions of limited connection between the interplanetary magnetic field and that of the Earth, one in the north and one in the south that are now separating, pulled apart by the magnetic stresses and carried by the magnetosheath flow (after Russell and Elphic [1978]).

The Reconnection Site

Much controversy has ensued about the underlying laws that control the rate of reconnection. One conjecture has been that magnetic fields reconnect most strongly when the magnetic fields are almost nearly antiparallel. Another conjecture is that reconnection takes place everywhere there is any antiparallel component, i.e. there is an angle of greater than 90° between them. While neither of these conjectures may be completely correct, they allow us to focus on differences in the magnetosphere that depend on the laws that govern the rate of reconnection. One of these differences is in the site of reconnection. This site is clearly observed to move. This motion is found when one uses the dispersion signatures of ions in the polar cusp to derive the distance to the merging site and it is seen in studies of the local time displacement of the polar cusp in response to a changing IMF By as shown in Figure 8. The simplest explanation of this motion, one that is consistent with MHD models, is that the reconnection site feeds the polar cusp and moves to the afternoon side in the northern hemisphere for positive By or to the morning side for negative By. While quantitative tests are not yet possible, at least qualitatively the reconnection site moves as if the reconnection occurred at the location of antiparallel magnetic fields.

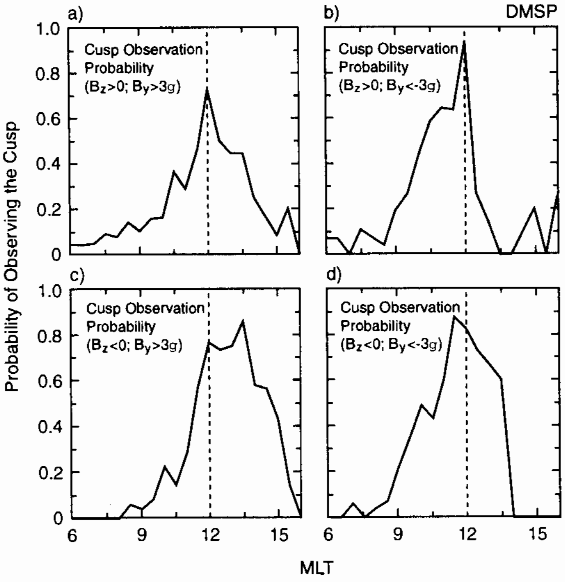

Fig. 8. *The probability of seeing the northern polar cusp in the ionosphere with the DMSP satellite as a function of local time and the direction of IMF [Newell et al., 1989]*

Most of these space observations were obtained with instrumentation developed and operated before the GEM began, although the ground-based program was active throughout the GEM period. Thus it was fitting, as new space data were beginning to appear from the Interball and POLAR missions, that the GEM Boundary Layer Campaign shifted from an NSF-managed program GEM to the IACG (Interagency Consultative Group). Thus the final discussions of the working group concentrated on first a review of the latest data from POLAR and Interball near the magnetopause and cusp, next on the theory of wave absorption on the cusp, and the use of ground-based pulsation data to identify the location of the boundary between open and closed field lines. While these presentations showed that our knowledge of the cusp and boundary layers continues to grow, it is appropriate that future coordination activities take place under the auspices of the IACG.

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3.3 Current Systems and Mapping

The objective of Working Group 3 was to provide an open forum for discussion and a venue for collaboration on problems concerning current systems associated with the magnetospheric boundary layers and concerning mapping between coupled boundary layer and ionospheric processes. The group focused primarily on transient phenomena and, of these, primarily on the ionospheric phenomenon called "travelling convection vortices," or TCVs. Working Group 2 had taken an early look at this phenomenon to determine whether a TCV was the ionospheric manifestation of a flux transfer event but, when this relationship did not pan out, Working Group 3 took the lead. As a result of this examination, a major evolution in understanding of TCVs and their relation to other transient phenomena was achieved.

At the start of the workshop series, TCVs had been identified in data from a meridional chain of magnetometers, and their motion away from noon along the polar cap boundary had been deduced from time variations at that meridian. Figure 9 shows the equivalent currents in the ionosphere as a TCV crosses the MACCS array. This array was established with the help of an NSF grant during the GEM campaign to study such phenomena at the boundary between open and closed magnetic fields [Zesta, in press 1999]. The successive panels show how the TCV grows and moves across the high-latitude ionosphere away from the noon sector. TCVs were thought by some to be the footpoints of field-aligned currents associated with the magnetopause phenomena called "flux transfer events," or FTEs. As data from more extensive magnetometer arrays and from complementary radar and optical sources became available, the working group became the focus of collaborative efforts to separate spatial from temporal effects and to relate TCVs to the growing array of other transient phenomena, for example, poleward moving auroral forms and progressing polar convection disturbances.

With the use of increasingly more sophisticated methods of handling two-dimensional data arrays, the realization gradually emerged that their sizes, forms, and movements are much more diverse than previously supposed. TCVs were found to travel nonuniformly along the polar cap boundary, if at all, and change shape as they travel. TCVs were found to occur in response to a number of different phenomena, and TCV signals from changes in the global convection pattern could be isolated from others by correlating with changes in interplanetary magnetic field (IMF) orientation.

Simultaneously with the observational efforts, the working group undertook several theoretical efforts. First, attempts were made to determine background convection patterns during selected TCV events using electric-field-mapping and empirical models with solar wind parameters as input. These efforts drew attention to the fact that TCVs occur during intervals of highly variable IMF orientation, which is a key input to the models, with the result that the entire concept of a background convection pattern was dismissed as useless. On the other hand, these efforts exposed aspects of the models ripe for improvements, some of which were incorporated in the course of successive workshops. In other theoretical efforts, insights into some forms of TCVs were gained through analytical modeling and through event studies using an MHD model.

In closing we note that Working Group 3 had its origins in a congenial group of researchers who fit around one table at GEM's 1990 Workshop on Intercalibrating Cusp Signatures. Most of these researchers worked with ground-based data and, as a result, already had extensive experience in collaborative efforts. They formed the core of Working Group 3, and, as the group rapidly expanded, their contagious community spirit expanded with it and became the group's hallmark. When in the course of GEM's policies the Boundary Layer Campaign drew to a close, an evolved core of Working Group 3 continued to meet under the extended wing of Working Group 1 for several more sessions. In view of its success as a promoter of community studies, it would be no surprise to find the core of Working Group 3 in some new incarnation as part of a future GEM Campaign.

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4. SECOND CAMPAIGN: MAGNETOTAIL AND SUBSTORMS (PHASE I)

One of the most difficult problems to solve in magnetospheric physics has been the physical processes that underlie the substorm, especially its onset. Thus it was most appropriate that the second GEM campaign focused on this problem

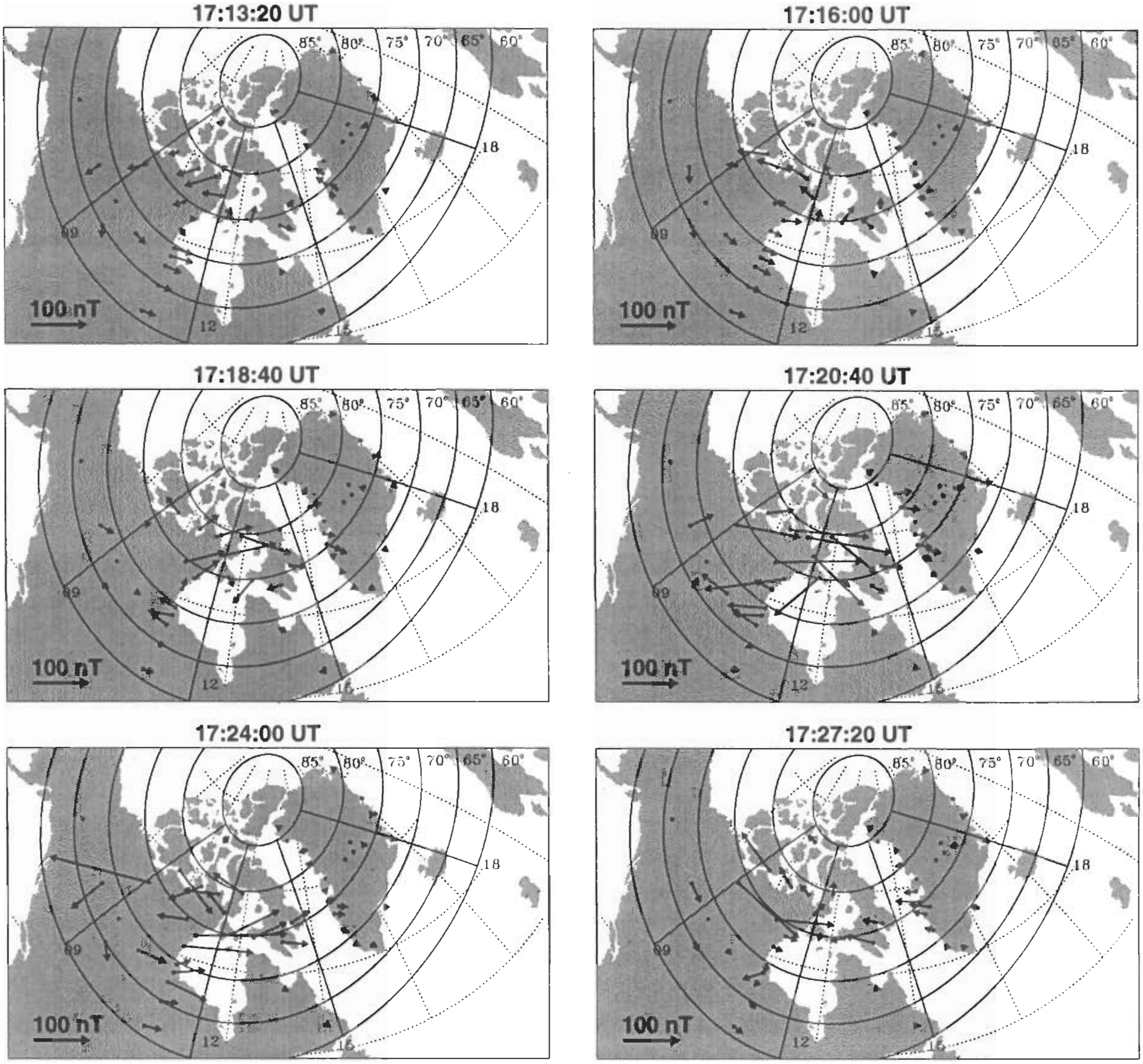

Fig. 9. Six successive maps of the high-latitude ionospheric current system deduced from the magnetic variation as Traveling Convection Vortex (TCV) crosses the MACCS array [Zesta, in press, 1999].

and its regions of origin, the magnetotail. Significant periods of the first two summer meetings were spent planning the Magnetotail/Substorms Campaign and reports were issued. In 1994 the first working meeting of GEM's second campaign was held.

4.1 Onset Signatures

Overview

Working Group 1 of the Magnetotail/Substorms Campaign was organized parallel to Working Group 1 of the Boundary Layer Campaign to emphasize substorm-related questions that could be addressed by coordinated data sets. It focused on the critical questions of the temporal and physical relationships between the diverse substorm phenomena that occur in different regions of the magnetosphere and ionosphere, especially during substorm onset and expansion. Its goal was to assemble coordinated data sets that could provide as definitive information as possible, and with which models of substorm processes could be tested and validated. The working group made considerable progress towards this goal; however much work remains to be done to obtain results that are as definitive and unambiguous as one would like. Progress has been limited by a lack of complete data sets in all regions and by sparse data coverage, which by necessity leads to a variable, but not well-known, lack of precision in identifying onset times and determining the relative timing of phenomena in different regions. However, this situation has recently improved with the explosion in data resources from the ISTP satellites. Working Group 1 has successfully promoted closer ties between the GEM and ISTP communities, and many on-going studies involve close cooperation and coordination between spacecraft and ground-based investigators. The GEM workshops are providing an excellent forum for GEM-ISTP coordination, and much further progress towards resolving timing ambiguities should be possible during the current ISTP era.

Areas of significant progress for the working group have been (1) the dynamics of the inner magnetosphere during onset and expansion, (2) the description and effects of bursty bulk flows in the magnetotail, (3) the connection of X-lines to substorm signatures, (4) possible ways to trigger substorms, and (5) the relationships and intercoupling between regions. As anticipated from such a challenging and multifaceted task, our results so far are not without some contradictions. They are presented below without prejudice. Further results can be expected, including resolution of conflicts, as many studies on the data sets assembled are ongoing, and vastly improved data resources have being available as a result of the international ISTP program.

At the conclusion of the 1997 workshop, the working group proposed the more focused goal to develop a phenomenological picture of substorms in time and space. This picture should be: (1) observationally based and not biased by particular substorm models, (2) eventually turned over to the GGCM community as a challenge for testing models, and (3) used to open doors for people (include those new to the substorm community) to add new information into the picture. This goal was adopted by the Steering Committee and new working group chairmen were selected to guide these efforts

Methodology

Working Group 1 concentrated on coordinated data-driven studies of substorms with the focus on the spatial/temporal relationships between phenomena in different regions. Using both ground-based and satellite data sets, it explored the timing of phenomena observed in the ionosphere, the inner magnetosphere, and the magnetotail to better define the phenomenology associated with pre-onset, onset, and the development of the substorm. To maximize data coverage, orbit prediction data were used to identify time intervals of confluence of satellites for space observations and then radar and other ground-based coverage were planned for these intervals. This maximized data availability and several, but not all, of the scheduled events were interesting from a geophysical standpoint. People with interest in the events then took the lead for subsequent data analyses. Other ad hoc events were found to give important contributions to our goals and some of these were added each year.

Workshop sessions were held at the Snowmass meeting in 1994, 1995, 1996 and 1997. In addition mini workshops were held in conjunction with the San Francisco AGU in 1994 and 1995. The group also sponsored a tutorial speaker each year at the Snowmass workshop.

Initial events were selected from the historical database of days with coordinated ground-based radar coverage. January 11-14, 1994 became a primary interval for study. As ISTP satellite data became more available during the GEM time period, the focus shifted from correlating ground-based data with polar orbiting and geosynchronous satellite data to coordinated events with the ISTP satellite suite. Nelson Maynard became the liaison between the GEM and ISTP communities. It was decided to exploit the WIND satellite perigee passes, which provides an additional source of near-tail data over a 12-hour period, and coordinated ground observations were planned for each of these events.

A list of GEM events from Working Group 1 with brief comments is found in the next section. Not all events have been exploited, nor should they be, because of lack of activity in some. However, the list constitutes a compendium of cases where extensive ground-based observations are available from the appropriate PI's for coordinated ground-based/satellite studies. The lead investigator is noted and brief synopses of results are included when studies have already led to publications. Further publications are anticipated from ongoing studies.

GEM Working Group 1 Event List

1) CRRES Events. (Two periods were selected as potential candidate events for the study of the timing of substorm onset signatures observed near synchronous orbit and from the ground around. Both included substorm onsets seen by the CRRES spacecraft near apogee (6.3 Re) and by the CANOPUS network of ground observatories. The data are primarily field and plasma data from CRRES, GOES magnetometer data and Los Alamos particle data from synchronous orbit, and CANOPUS meridian scanning photometer and magnetometer data. For each event the question was then asked: Is this data set useful for addressing one of the questions identified as important for the Magnetotail/ Substorms Campaign?

24 Jan 1991, 0802UT

At 0802UT a well-defined onset occurred in the magnetometer and photometer data from Fort Smith and Fort Simpson in the Yellowknife sector and close to the foot of the CRRES field line. Effects at CRRES (magnetic field dipolarization, electron injection), and at the two GOES spacecraft located roughly an hour in local time either side of CRRES, occurred some five or six minutes later. Since the ground onset was observed so close to the nominal foot of the CRRES field line, it was felt that this event would provide a good case study for examining delays between ground and synchronous orbit signatures. W. J. Hughes led this study.

9 March 1991, 0602UT

An onset occurred at 0602UT when CRRES and GOES 7 were very close, and within uncertainties, in the same meridian plane, very close to the CANOPUS Churchill meridian chain of magnetometers and photometers. An auroral brightening and poleward expansion as well as Pi2's were seen on the ground. Both CRRES and GOES 7 observed dipolarizations and FAC signatures, while CRRES wave and plasma data also had good signatures. Even though this was a weak substorm (almost no AE signature and only small auroral magnetogram bays) the consensus was that the very close conjunction of two s/c at onset made this event interesting, as it allows study of the spatial and temporal structure of synchronous dipolarizations. Hughes and H. J. Singer were the study leaders.

Additional CRRES results

In addition to the above events, GEM collaboration led to a coordinated study of other events using CRRES and ground-based data. This study led to an empirical scenario for substorm onset. The process grows from ripples at the inner edge of the plasma sheet associated with dusk-dawn excursions of the electric field, prior to the beginning of dipolarization. Energy derived from the braking of the inward plasma convection flows into the ionosphere in the form of Poynting flux. Subsequently reflected Poynting flux plays a crucial role in how events unfold. Substorms develop when significant energy (positive feedback) flows in both directions, with the second cycle stronger than the initial. Pseudo breakups occur when energy flow in both directions is weak or out of phase (negative feedback).

Figure 10 shows the field-aligned Poynting flux observed at the start of an isolated substorm. Negative values are toward the ionosphere. The initial downward flux follows dusk-dawn electric field excursion E. Following the return flux from the ionosphere, the large flux after excursion F lead to the rapid dipolarization at CRRES and intensification on the ground. Ground onset was just after excursion E. Excursion B is an example of energy flow toward the ionosphere with no return. The result was a weak Pi-2 and pseudobreakup.

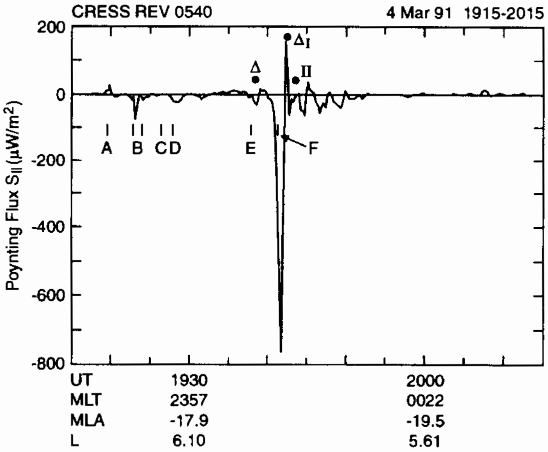

Fig. 10. *The component of the Poynting flux along the magnetic field for event 540. Positive (negative) flux is directed away (towards) the ionosphere. The times of dusk-dawn excursions of the electric field are denoted by the letters A-F. The substorm was triggered by excursion E. Particle injection at CRRES is marked by Π. Δ shows the beginning of dipolarization. [Maynard et al., 1996a].*

Heated electrons arrive at the spacecraft at least five minutes after initial activity while convection is earthward, during or at the end of electromagnetic energy flow away from the ionosphere. Observations indicate that the dusk-dawn excursions of the cross-tail electric field correlate with changes in currents and particle energies at CRRES and with ULF wave activity observed on the ground. Magnetic signatures of field-aligned current filaments associated with the substorm current wedge were observed to be initiated by this process. Variations of the electric field and Poynting vectors with periods in the Pi2 range are consistent with bouncing Alfvén waves that provide electromagnetic communication between the ionosphere and plasma sheet. High-resolution electric field measurements from one case shows that the principal Poynting flux communicated between the ionosphere and the magnetosphere is in the Pi2 frequency range [Maynard et al., 1996a,b].

2) GEOTAIL flow studies for 11-14 Jan. 1994 GEM interval (Angelopoulos). A series of tailward-to-Earthward particle anisotropy reversals were observed by the GEOTAIL spacecraft in the distant magnetotail plasma sheet at a distance of X ~ = -90Re during the 2.5-day period from 1200 UT on 11 January, 1994, to 2400 UT on 13 January, 1994 [Angelopoulos et al., 1996]. The X-component of the cross-field flow exhibits the clearest indicator of a particle anisotropy reversal. A comprehensive examination of ground magnetometer and geosynchronous satellite data reveals that each distant tail anisotropy reversal occurred during the late expansion or recovery phase of a magnetospheric substorm. Out of 14 substorms during which adequate monitoring of the geomagnetic activity and the plasma sheet was possible all but possibly one exhibited a tailward-to-Earthward reversal in the cross field flow ~1-2 hours after substorm onset. The median time delay between substorm onset and the beginning of the subsequent Earthward convective flow was 94 min. Some uncertainty is associated with this time delay due to the commonly observed exits of the spacecraft; to the lobe/mantle. The lower limit on the time delay based on the time of exit of the spacecraft to the lobe/mantle is 61 min.

3) Detailed study of 14 Jan. 1994, 0629 UT onset and 18-21 UT activity interval comparing GEOTAIL with ground observations (Maynard). This study emphasized the relationships of X-lines in the tail to the aurora near the high-latitude boundary of the aurora in the ionosphere [Maynard et al., 1997, 1998; Burke et al, 1998]. GEOTAIL plasma and field measurements at -95 Re were compared with extensive ground-based, near-Earth and geosynchronous measurements to study relationships between auroral activity and magnetotail dynamics during the expansion phases of two substorms. The studied intervals are representative of intermittent, moderate activity. The behavior of the aurora and the observed effects at GEOTAIL for both events are harmonized by the concept of the activation of near-Earth X lines (NEXL) after substorm onsets with subsequent discharges of one or more plasmoids down the magnetotail. The plasmoids must be viewed as three-dimensional structures, which are spatially limited in the dawn-dusk direction. Also, reconnection at the NEXL must proceed at variable rates on closed magnetic field lines for significant times before beginning to reconnect lobe flux. This implies that the plasma sheet in the near-Earth magnetotail is relatively thick in comparison with an embedded current sheet and that both the NEXL and distant X line can be active simultaneously. Until reconnection at the NEXL engages lobe flux, the distant X line maintains control of the poleward auroral boundary. If the NEXL remains active after reaching the lobe, the auroral boundary can move poleward explosively. The dynamics of high-latitude aurora in the midnight region thus provides a means for monitoring these processes and indicating when significant lobe flux reconnects at the NEXL.

4) Electric field changes relative to onset using Goose Bay and Sondrestrom observations during March 1993 GEM interval (Lyons). These substorms were part of a study for measurements of the nightside reconnection rate during the course of substorms, which included data from 20 nights, most of which are during GEM campaigns. The average nightside reconnection rate was found to increase within 5 min of substorm expansion phase onset. In individual cases, such an immediate increase in the reconnection rate was found to occur only near midnight. Farther from midnight, the reconnection rate does not increase until 20 min after onset, on average [Blanchard et al., 1997].

5) Classic isolated substorm at 0430 UT on 9 Feb. 1995 with comprehensive ISTP observations (Lui). An extended interval of a strong northward interplanetary magnetic field (IMF) was observed by the Wind spacecraft located at an upstream distance of ~193 Re from February 8-10, 1995 with a brief break of southward IMF from 02-04 UT on February 9. This brief interval of southward IMF led to an isolated substorm of moderate intensity (~500 nT) with the expansion phase starting at ~0431 UT. This substorm may be triggered by a northward turning of IMF since its onset time matched well with the time expected for the arrival of northward turning of IMF at Earth. Substorm activities were monitored by 11 spacecraft (Wind, IMP-8, Geotail, six geosynchronous satellites, one DMSP satellite, and Freja) and two networks of ground stations (Canopus and SuperDARN) covering both the northern and southern hemispheres. The extensive coverage of this event provides results (1) showing some unusual characteristics possibly related to the isolated nature of the substorm, and (2) revealing some surprising features difficult to reconcile with the traditional substorm model. In the first category are the unusually long duration of the growth phase and the long time delay between substorm expansion onset and particle injection onset at the geosynchronous orbit. In the second category is new evidence for multiple particle acceleration sites during substorm expansion and for sunward flow during the late expansion phase of a substorm being not related to a single acceleration site (X-line) moving from the near-Earth tail to the more distant tail. We also present observations that show the possible optical signature on the ground of bursty bulk flows in the magnetotail. [Lui et al., 1998]. The dynamics of this isolated substorm observed on Feb. 9, is also examined by Winglee et al. [1998] using global simulations along with the in-situ observations from WIND, Geotail, and IMP-8, and ground-based observations from CANOPUS.

6) Nice isolated substorm of March 9, 1995, at 0248 UT with excellent ISTP data and a 1 hr and 20 min growth phase (Rodger). The Wind spacecraft, about 200 Re upstream in the solar wind near the sun-Earth line, detected a rapid southward turning of the interplanetary magnetic field at 0248 UT on 9 March 1995, after an extended interval (>24 hours) when the field had been northward. Therefore the magnetosphere was close to a quiescent state. One hour after the southward turning, a relatively simple and extended growth phase started that terminated with substorm onset near 0500 UT. At this time, Geotail and IMP-8 were located in the nightside magnetosphere near the equatorial plane at -13 and -30 Re, respectively, and therefore were ideally placed for making critical measurements in each of the three accepted phases of the substorm. The activity was centered over North America and the North Atlantic in the northern hemisphere, and the Weddell Sea Sector of Antarctica in the south: areas that are very well instrumented with magnetometers, all-sky imagers, riometers, and the SuperDARN radars. These high time-resolution space- and ground-based data of outstanding quality when combined with the LANL, GOES and DMSP spacecraft data, are likely to provide a unique view in latitude, longitude and altitude of this comparatively simple substorm. The results from this study should be of considerable value in the identification of successful features and limitations of the various competing substorm models.

7) Two ISTP events with good radar coverage, Sondrestrom imager data, and GEOTAIL in the center of the tail at 25 Re (Sanchez). Magnetosphere-ionosphere coupling of onsets to be studied. Onsets at ~2245 UT on 7 Feb. 1995, ~01 UT on 8 Feb. 1995, ~23 UT on 23 Feb. 1995, and ~0310 UT on 24 Feb. 1995.

The following are GEM intervals centered around the WIND perigee passes. GEM solicited ground-based observations to support interesting satellite configurations that occurred during the WIND perigee passes through the near magnetotail. The spring 1996 WIND perigee passes added POLAR plasma, field, and imaging to the ISTP fleet as well as the usual geosynchronous satellites and DMSP. A number of these events were extensively discussed. The following list records significant events detected on WIND during these intervals. Additional comments have been added as appropriate along with results from completed studies.

8) September 16, 1995: WIND B-field dipolarizations at X = -13 Re during 2200 - 2400 UT substorm. GEOTAIL observing IMF (Sanchez). Initiating study of 2215 UT onset on Sept. 16. 1995. WIND saw dipolarization at ~2245 UT.

9) November 29, 1995: WIND B-field dipolarizations at X = -12 Re during 0030, 0630 and 0740 UT substorms. GEOTAIL is at the dawn magnetopause/magnetosheath. Good Greenland data for first event. IMP-8 IMF (McPherron). Studied 0353 UT onset on Nov. 28, 1995. Found that GEOTAIL at x = -30 Re saw tailward flow for 15 min prior to onset. At the same time B was almost entirely in the y direction.

10) January 13, 1996: WIND B-field dipolarization at X = -11 to -12 Re during 0300 and 1530 UT substorms. GEOTAIL skimming the dayside magnetosphere. First event has multiple injections. SuperDARN good for entire period. Greenland good. Effects seen at INTERBALL. (Greenwald). Day-night comparisons possible on second substorm. This study builds on a study of mesoscale dayside convection vortices and their relation to substorm phase [Greenwald et al., 1996].

11) March 27, 1996: WIND and GEOTAIL B-field dipolarization at X = -15 Re and -18 Re respectively during 0940 UT substorm. INTERBALL in solar wind. POLAR imaging. 0925 pseudo breakup followed by a big breakup at 0945. Also events at 2200 to 0300 on the 28th. (Angelopoulos). A series of bursty-bulk-flow events (BBFs) were observed by GEOTAIL and WIND in the geomagnetotail. IMP 8 at the solar wind showed significant energy coupling into the magnetosphere, while the UVI instrument on POLAR evidenced significant energy transfer to the ionosphere during two substorms. There was good correlation between BBFs and ionospheric activity observed by UVI even when ground magnetic signatures were absent, suggesting that low ionospheric conductivity at the active sector may be responsible for this observation. During the second substorm no significant flux transport was evidenced past WIND in stark contrast to GEOTAIL and despite the small intersatellite separation (3.54, 2.88, -0.06) Re. Throughout the intervals studied there were significant differences in the individual flow bursts at the two satellites, even during longitudinally extended ionospheric activations. It was concluded that the half-scale-size of transport-bearing flow bursts is less than 3 Re [Angelopoulos et al., 1997].

12) April 18, 1996: WIND and GEOTAIL B-field dipolarizations at X = -12 and -14 Re during substorms at 0500, 0730, and 1030 UT. Separation of 1 Re in X and Z and 10 Re in Y. INTERBALL and IMP in solar wind (Slavin). After onset at 0725 UT, dipolarization began at GOES 9 immediately. A series of rapid Bz increases were observed at WIND and GEOTAIL approximately 25 to 30 minutes later. Approximately 1 to 2 minutes before each of these events an earthward flow burst with peak speeds of 100 to 500 km/s were observed. The duration of these bursty flows was 1 to 7 minutes. These observations were interpreted as strong evidence of spatially localized, but sometimes temporally overlapping flow bursts in the near tail during the substorm expansion phase. These observations confirm the relationship of bursty flows and local dipolarization and show evidence of azimuthal spreading with local time of the flow events [Slavin et al., 1997].

13) May 10, 1996: WIND B-field dipolarization at X = -12 Re during 0400 substorm. GEOTAIL in dayside magnetosphere. Apparently no solar wind data (IMP data gap). GOES dipolarization at 2300 local. 0400 injection at geosync. 0359 onset in POLAR images. INTERBALL 0400 magnetopause crossing.(Greenwald, Reeves). Good radar data. The WIND data set has also been used by Parks et al. [1997] to investigate ion beams in the near-Earth plasma sheet during the passage from the plasma sheet into the lobe. Plasma consists of cold and warm components with an additional hot component as the satellite approached the interface to the lobe. Beams originate from the warm component, which is the most dynamic. Both earthward and tailward travelling beams were seen. Beam generation from an X-line and from the ionosphere were considered with the opposite directed beams being reflections. Parks et al. [1998] published a follow up paper.

Other ISTP periods

14) January 1,2, 1997 (Fox and Lui). GEOTAIL and IMP cross midnight together at ~30 and ~ 38 Re. There were small onsets at ~2145,and 2200 on the 1st, and a well-defined but moderately small onset at 0157 on the 2nd. During the ISTP interval of Jan 1-2, 1997, Geotail and IMP-8 were closely aligned in the midnight sector of the tail region at the downstream distance of ~30 Re. This fortuitous alignment offers an opportunity to examine the occurrence of a near-Earth neutral line relative to substorm expansion onset. Two substorms were identified by global auroral observations from POLAR and ground-based stations - one initiated at 2145 UT on January 1, 1997 and the other at 0145 UT on January 2, 1997. Preliminary analysis of these two substorms suggests that the near-Earth neutral line signatures did not occur until well after the expansion onset times. Data are at http://www-spof.gsfc.nasa.gov/istp/events/gem. A copy of this website has also been archived on the CD-ROM that accompanies this report.

15) April 7-11, 1997, (Foster, Lyons, Fox). This is a good period for studying IMF-substorm relations for non-ideal events, because of good ground and IMF coverage on April 10 and 11. Significant data sets are posted on the web at http://www-spof.gsfc.nasa.gov/istp/event_apr97/index.html. A copy of this website has also been archived on the CD-ROM that accompanies this report.

16) A substorm onset study looking for evidence of triggering involving many of the above events (Lyons). To understand the magnetospheric substorm, it is necessary to determine whether its onset is externally triggered by the interplanetary magnetic field (IMF). The relationship between the IMF and the onset of classical substorms with well-defined onset times was analyzed. A classical substorm is one that has auroral brightening and electrojet formation at onset, followed by poleward expansion of the region of bright aurora. Substorms meeting these criteria were identified using CANOPUS ground photometer data. A clear IMF trigger (a northward turning or a reduction in the magnitude of the y component) could be identified for 14 of the 20 substorms used in the study. All but one of the identified triggers are northward turnings. A rigorous set of criteria that represents these triggers was developed. By applying the criteria to a large set of IMF data, it was determined that it is essentially impossible for the observed association between triggers and substorms to happen by chance. This demonstrates that substorm triggering is a real phenomenon and not the result of the requirement that the IMF be southward before but not after a substorm. The spatial structure in the plane perpendicular to the Earth-sun line critically affects whether or not a trigger is observed from a particular IMF monitor. The probability of seeing a trigger for the substorms in our study is 89% for monitors that are < 30 Re from the Earth-sun line but only 50% for monitors 30 Re to 56.7 Re from the Earth-sun line. Thus a well-defined IMF trigger is associated with most of substorms considered here, and the probability of trigger identification is a strong function of IMF monitor distance from the Earth-sun line. Given this limitation of trigger identification due to spatial structure, the observations imply that a large majority of classical substorms are triggered by the IMF. Estimates of ~9 min for the mean time delay between magnetopause contact of an IMF trigger and substorm onset and ~64-72 min for the median growth phase period of southward IMF that precedes triggered classical substorms were found [Lyons et al., 1997].

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4.2 Magnetotail/Substorm Phenomenology – Observations and Models

Overview

The Magnetotail/Substorms Working Group 2 was organized as the fulcrum between the primarily observational focus of Working Group 1 and the primarily theoretical focus of Working Group 3. It explored the important middle ground and promoted the combination of models and data in order to facilitate the quantitative testing of current magnetospheric models. In so doing, it promoted discussion of model capabilities and limitations as well as data constraints and limitations. The working group was not very reliant on specific event studies, but rather focussed on important outstanding questions for which either observations, models, or both were lacking or deficient. As Working Group 2 reached maturity in its third and final year of existence, several topics ripened and flourished. One in particular (substorm triggering) led to prominent notoriety not only within the space science community, but also within the broader science community (as measured by publications in Science and EOS).

History

The working group's philosophy was to promote a "roundtable" workshop atmosphere, where a series of short presentations provided ample opportunity for full audience participation. This atmosphere led to lively discussion with enough time for important issues to be addressed in depth. These "rules" proved to be fertile ground for stimulating new GEM-related collaborations, which is an extremely important aspect of the GEM program. This philosophy underscores the vital importance of the GEM workshops to its overall success.

Working Group 2's inaugural meeting occurred at the 1994 GEM Snowmass Workshop with three sessions during the second half of the week and a sponsored invited talk during one plenary session. It then met on the Sunday prior to the fall 94 AGU meeting to discuss magnetotail/substorm phenomenology and to explore additional model/data comparisons.

During subsequent summer Snowmass Workshops in 1995 and 1996 these ongoing topics and data/model comparisons reached their maturity. Owing to its overlapping interests with Working Groups 1 and 3, the working group met jointly with them as the campaign progressed. These times of overlap provided important opportunities for the often-disparate communities to meet together and discuss the same science topics under one roof. Additionally, Working Group 2 used the GEM Workshop as an instrument to promote cross-program connections. At the 1996 summer workshop, the working group highlighted the present and future contributions of GEM to the GGS, STEP, and IACG programs, extending its data/theory connections beyond the walls of the GEM program to the international community. These connections garnered excellent scientific participation from international scientists whose ground-based and space-based data and models provided new resources for the GEM program.

In 1997, the Magnetotail/Substorms Campaign structure was reconfigured in light of the introduction of the Inner Magnetosphere and Storms Campaign's commencement. As a result of this natural evolution, the format of the Magnetotail/Substorms working groups was realigned. Many aspects of former Working Group 2 remain in the current GEM program, redistributed in the newly formed working groups. Therefore, in this report, the focus is on those topics explored by the working group from 1994 through 1996.

Science Highlights

The working group focussed on all aspects of magnetotail modeling, including not only the most explosive phases of the substorm process, but also including the most quiescent periods that bridge the periods of dynamism. The science topics were directed to some degree by the working group chairs and steering committee, but to a large degree, they were motivated and led forward by the interest and energy of the GEM participants. The discussion areas, noted below, reflect the working group's interest in both magnetotail dynamics and magnetotail structure. While individual workshop sessions may have carried slightly more focussed titles, the three years can be summarized collectively by the four following research areas:

- MHD versus Kinetic Aspects of Magnetotail Plasma Sheet Modeling
- Magnetotail Geometry and Substorm Triggers: Theoretical Predictions and Observational Constraints of IMF Control
- Plasma Sheet Plasma Sources
- Specific Model Predictions and Data Comparisons

MHD versus Kinetic Aspects of Magnetotail Plasma Sheet Modeling

Under this umbrella, several studies explored the conditions for which fluid modeling and kinetic modeling are appropriate for describing the tail plasma sheet quantitatively. These studies are critical for the ultimate development of any robust GGCM. Dissipation processes in the thin boundary regions of the magnetosphere are not described by simple MHD fluid models, nor can the full physics treatment of kinetic models be reasonably applied to the complete magnetosphere at this time. Accordingly, we need to understand where and when the two approaches are relevant and how we can begin to merge the two approaches. During the M/S Campaign, several early attempts of blending these models were begun.

The specific science topics in this area ranged from the macroscopic characterization of chaotic and "Speiser" orbits for plasma sheet models, to the role of single particle motion in thin current sheets to microscopic and macroscopic plasma effects, to the comparison of both global fluid and local kinetic models with spacecraft observations, to a discussion of the limitations and constraints of ideal MHD. One significant result arising from the deliberations of the working group was reported by Usadi et al. [1996] who explored the question "How bad is bounce-averaged drift in the context of chaotic/Speiser-type orbits?" This work demonstrated that even in regions where non-MHD effects can be large, a fluid-like description of the plasma may still be effective in describing many of the more important properties of the plasma sheet plasma. At the other scale-size extreme, Kaymaz and Siscoe [1998] demonstrated that properly sorted statistical models of magnetic field structure in the mid-tail are reproduced excellently by MHD model snapshots of the same region. These successful model/data comparisons suggested an entry of plasma into the magnetotail, not exactly consistent with simple vacuum merging, and leading to our present GEM-driven understanding of the magnetospheric "sash" [White et al., 1998].

Magnetotail Geometry: IMF Control and Substorm Triggers

A particularly challenging problem in magnetotail modeling is to accurately predict the location and timing of the instability accompanying substorm onset. There have been long-standing debates on this issue, focussing on different aspects of the problem: directly driven versus loading-unloading, internal trigger versus external trigger, global versus local instabilities. Working Group 2 concluded that this was an area primed for new progress within the GEM program. New missions providing better suited data and improved theoretical understanding had been acquired since most of the seminal work in this area was completed decades before. In 1994, it held its first discussions on this topic. Topics included all possible sources of control and triggers including the areas of M-I coupling; this area drew on the experience gained from the first GEM campaign. Over the course of the campaign, the sessions motivated several very fruitful studies. As the topic matured, the focus was on IMF control and substorm triggers.

Archival missions, recent GEOTAIL and other ISTP data were critical to many of the studies reported on by this working group. Special extreme cases of magnetospheric configuration were investigated using these data [Fairfield et al., 1996]. For example, the magnetotail topology was explored during a period of unusually prolonged and strongly northward IMF for which the absence of a nominal tail was observed (a downtail radius of only 10 Re was inferred). This rather extraordinary type of extreme event proved to be very beneficial for possible comparison with MHD models driven with the same sort of simplified solar wind input conditions [Raeder et al., 1995]. Such events served as data "challenges" that were posed to the Modeling Working Group.

A very rich area for discussion and progress was revisiting the controversy of northward turnings of the IMF as a trigger for substorm onset. At the 1994 session, R. L. McPherron reviewed the past history of this topic, noting that ~50% of substorms could be associated with a northward turning of the IMF within a five-minute uncertainty in timing. At the same meeting, S. M. Petrinec and C. T. Russell explored the role that sudden impulses might have on substorm triggering using a data-driven, pressure-balanced magnetopause model. The session concluded that the new data provided by ISTP, both in terms of IMF coverage and onset timing, were available now to make progress.

At subsequent summer workshops, where, results of many studies were vigorously debated, sessions were devoted to identifying measurements that could be used to quantitatively test specific predictions regarding substorm triggers. The presentations and discussion covered both theoretical and observational aspects. In the case of theoretical presentations, an attempt was made to solicit not only a trigger scenario and its mechanism, but also to identify an unambiguous observational signature predicted by the model. Notable among these was the premise proposed by L. Lyons that substorms are always triggered by a reduction in |Bz| or by a northward turning. This prediction was referred to as "The Strong Snowmass Conjecture." Lyons showed several cases that argued for a northward turning onset trigger and presented a model that invoked limitations of particle access to the inner edge of the plasma sheet during rapid changes in the magnetotail electric field. A need for further quantification of this conjecture and observational tests were stressed.

V. Sergeev pointed out the importance of accurately tracking isolated features in the solar wind for such IMF timing studies. Availability of ISTP data was critical for this analysis. It was stressed that two satellites in the solar wind are necessary to determine properly the orientation of the discontinuities. Delays of up to 20 minutes are possible between when a discontinuity detected upstream actually reaches the magnetosphere and when it would be predicted based on an assumed discontinuity normal direction along the solar wind flow direction.

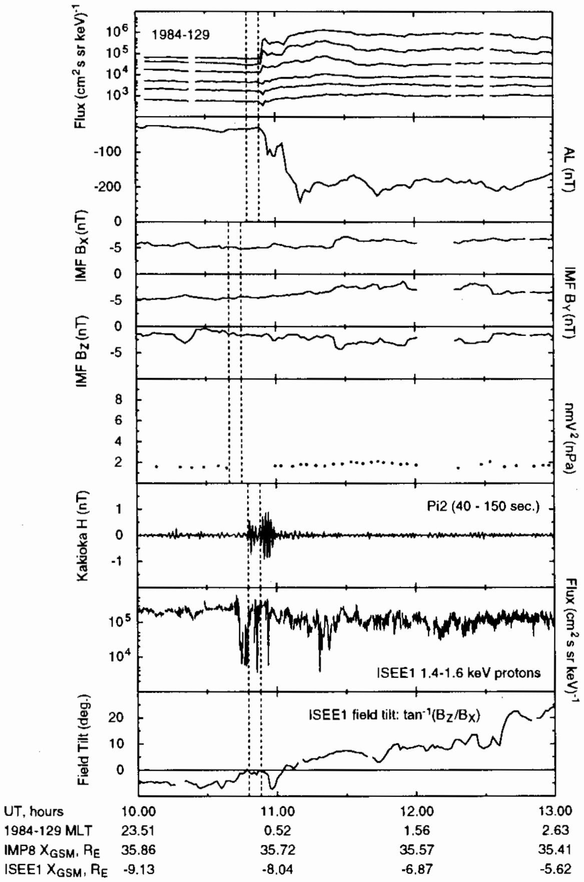

Fig. 11. Evidence for a spontaneous substorm. Top panel shows energetic particle fluxes measured in synchronous orbit by the spacecraft 1984-129. Beneath this panel is the AL index showing an increase in auroral currents when the energetic particles were injected. During this time shown in the panels further down the IMF and the solar wind dynamic pressure show almost constant values and in particular no northward turning from its southward orientation. The bottom three panels show the onset time determinant from Pi2 measurements and changes in the plasma sheet protons and magnetic field at the substorm onset as seen by ISEE 1 in the near tail. The local time of 1984-129 and the X GSM locations of IMP in the solar wind and ISEE in the tail are given below the diagram [after Henderson et al., 1996a].

Owing to these discussions, GEM elevated this topic to the forefront. Several groups stepped forward to address the "Snowmass Conjecture" results, suggesting cases where no IMF trigger was found [e.g., Henderson et al., 1996a; 1996b, Angelopoulos et al., 1996]. Figure 11 shows evidence for one such spontaneous substorm that is particularly well documented with data in the auroral zone, the near tail, synchronous orbit and the near solar wind [Henderson et al., 1996a]. Figure 12 shows the accompanying auroral expansion seen from space by the Viking spacecraft. The topic gained the attention of EOS and several short papers outlining the issue were published as part of the series of "Great Debates in Space Physics" [Spence, 1996; Lyons, 1996; Lui, 1996]. The debate on the veracity of the Snowmass Conjecture was highlighted eventually in Science [Kerr, 1996] and led to important publications in refereed literature. While much progress was made on this topic, it was clear that we are still inherently limited by available data, both in the solar wind and in the magnetotail. The need for better timing of substorm phenomenon, a key element of the debate, became the focal point for a current Magnetotail/Substorms Working Group, illustrating the fluidity of the GEM program to evolve as studies mature.

Plasma Sheet Plasma Sources

Another topic promoted within Working Group 2 was the sources and entry of plasma to the magnetotail plasma sheet. In 1994, the then-recent GEOTAIL mission again provided invaluable insights into this topic and active participation by Japanese and other scientists at the GEM meeting should be especially noted. This topic benefited from excellent review presentations of past and present missions. These presentations identified the LLBL as an important entry portal of magnetosheath plasma onto closed magnetospheric field lines. M. Fujimoto and M. Nakamura presented observations clearly showing mixing regions where magnetosheath and magnetospheric plasmas co-exist in the magnetotail. Models describing the motions and access of particles within the magnetotail using single-particle motion and bounce-averaged drift physics were presented by H. Spence and T. Onsager.

Model Predictions and Data Comparisons

The other major effort sponsored in part by Working Group 2 was to encourage scientific closure through the comparison of model predictions with relevant observations. The goal of the workshop sessions was to identify specific predictions of magnetotail structure or dynamics models and to identify observations that could be used to test the models and to differentiate between features of similar models. Some participants compared their model results with data, while others made predictions that could be tested in the near future. Many collaborations were galvanized in these sessions. Owing to the overarching theme of this broad topic, the working group benefited greatly from overlap with the other two Magnetotail/Substorms working groups.

The use of global MHD models to predict substorm features was explored by an excellent cross-section of modelers (J. Lyon, J. Raeder, J. Birn, M. Hesse, and R. H. Winglee). Lyon and Raeder illustrated the global nature of the substorm process as revealed in MHD simulations and noted the particular difficulty of timing from simple spacecraft studies. Many of the signatures associated with substorm onset occur nearly simultaneously in the near-Earth region. In these models, the substorm involves a global loss of equilibrium, making a comparison of events detected by spatially separated spacecraft very difficult to compare quantitatively with the simulations.

Birn used his results from 3D simulations to make certain new observational predictions from a more localized perspective. A specific prediction of this model is that the cross-tail current diversion occurs along sheets located roughly in x-z planes with large local-time extent, rather than at the local-time edges of the current-diversion region. Hesse used results from a 2D hybrid code to explore observational features associated with thin current sheets known to exist just before substorm onset. His two main points were that only a small fraction of the electric field penetrates into the central

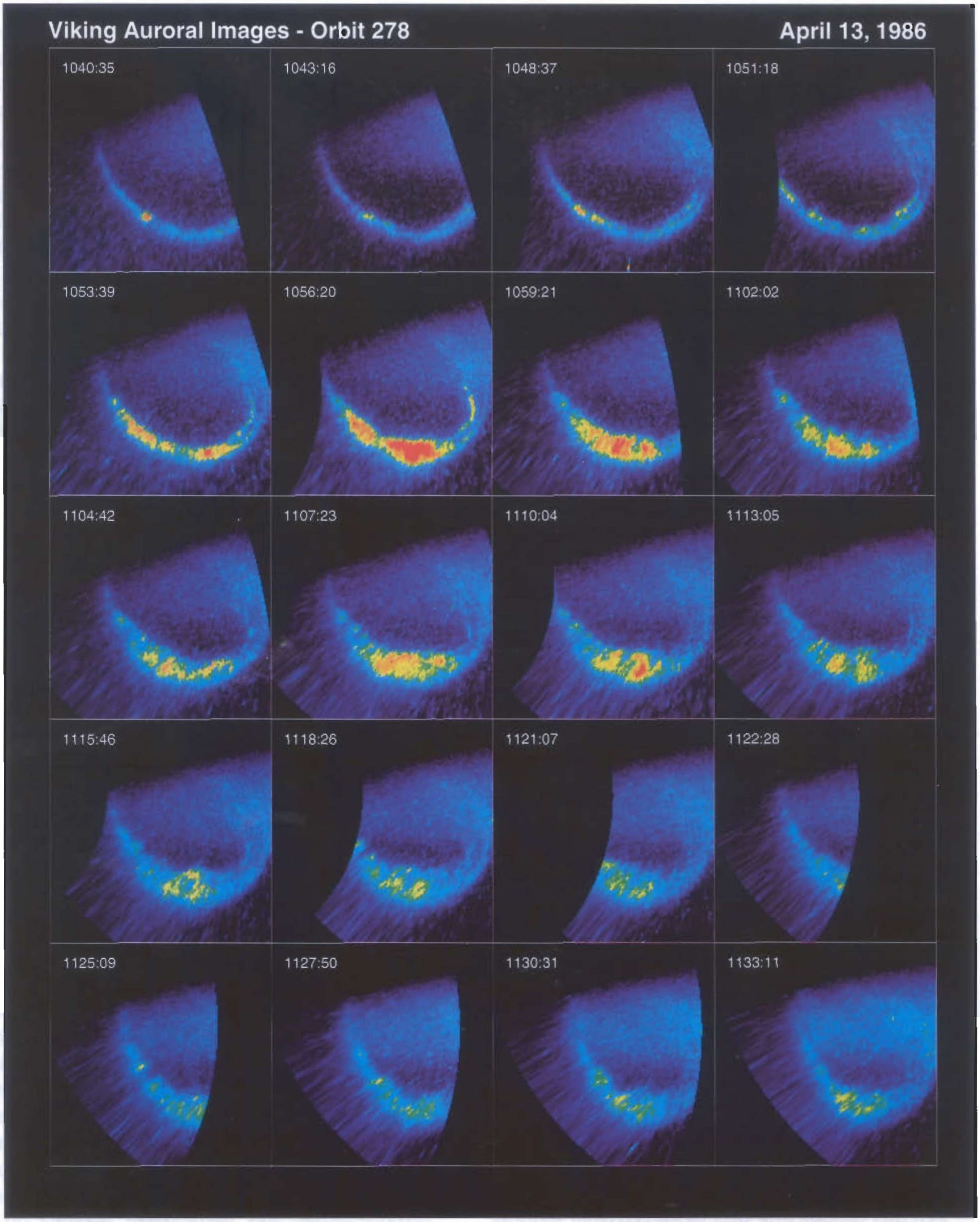

Fig. 12 Auroral expansion as seen by the Viking spacecraft for the substorm illustrated in Figure 11 [Henderson et al., 1996a].

region of the simulation where the thin current sheets form (inductive fields are large), and that the current within the thin sheets is carried predominately by the electrons.

Winglee and his group reported on output from their global 3D MHD code. This code includes two-fluid effects. They investigated the location of auroral currents and the equatorward edge of the evening auroral oval as a function of IMF and solar wind dynamic pressure. One specific feature is that cusp currents form in the 2-fluid simulation that are not present in MHD simulations. In another study, the magnetopause position predicted by the MHD code was compared with observed crossings. They demonstrated that the magnetopause locations obtained from his code for a wide range of solar wind parameters agreed well with the average locations determined by the empirical models of Petrinec and Russell and by Roelof and Sibeck.

Non-MHD models were also highlighted in our discussions. A. Lui presented a number of features of his current disruption scenario for substorms. One testable prediction is the presence of broadband whistler waves in the current sheet at the time of current disruption. The whistler waves are also predicted to shift in frequency as current disruption progresses. T. Speiser described a model for ion distributions that should be found in the vicinity of near-tail reconnection sites. R. Wolf proposed a test of the Magnetospheric Specification Model using measurements from GEOTAIL to predict geostationary fluxes. These studies are in various stages of completion.

Finally, empirical magnetic field models were tested by G. Reeves. Static magnetic field models were assessed using DMSP low-altitude particle data with in situ geosynchronous satellite data. By comparing the particle spectra measured by DMSP as a function of latitude with data at geosynchronous orbit, the approximate conjugate locations were determined empirically. These results were then compared with the field-line mapping given by many different static magnetic field models.

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4.3 Quantitative Magnetotail and Substorm Models

Working Group 3 of the GEM Magnetotail/ Substorms Campaign was charged with the investigation and development of quantitative tail and substorm models, in support of the development of a General Geospace Circulation Model. The complexity of the tail structure and dynamics necessitates an understanding of a variety of source mechanisms, coupling mechanisms, and of the interaction between small and large-scale processes. Beyond that, it was felt that magnetotail structure, at both quiet and active times, required further investigations. These topics formed the basis of the discussion topics selected during the review period.

The discussion was structured into at least half-hour segments. During each segment a prescheduled discussion leader pursued a particular subtopic, usually by presenting concepts, models, and/or results to inform and stimulate the discussion. This format seemed to work well. The discussions were very lively. Strengths and weaknesses of various models were identified, and, in at least one critical area described below, no adequate models were found to exist. Although the theoretical discussion sometimes proceeded without consensus, occasional interjections by observational researchers provided an essential reality check.

Magnetotail Equilibria and Structure

The objective of studying equilibrium models is to determine the influence of boundary conditions on the tail structure by examining the tail in approximately equilibrium conditions. It was found that nightside region 1 currents were primarily in the region surrounding the boundary between open and closed field lines where the shear in B_y was large. It is likely (although not included in the equilibrium model) that these currents originate along the tail flanks. This raises the question, “How does the magnetostatic tail field compare with (1) global MHD and (2) with the IMP statistical tail?” It remains to be resolved as to how, when the boundary conditions are continuously varied, does a loss of equilibrium lead to the formation of a thin current sheet and substorm onset? Although it is not clear at this time how to incorporate equilibrium models into a "substorm module," a simplified equilibrium pressure distribution characterizing the tail may allow a quick determination of substorm onset for given solar wind conditions.

The inner plasma sheet/outer ring current region is important because it maps into the auroral region and is the likely site of substorm onset.

This is difficult to do because in this overlap region neither the simplifying tail approximation given above nor the low beta drift physics approximation can be used. L. R. Lyons has conjectured that plasma in the tail may require a plasma source and the mantle may be the most important source. A serious deficiency is that no existing models treat this region adequately.

Scale-Interactive Processes

Including non-MHD processes in MHD

It is important to determine what processes are significant in coupling with the MHD model. To determine what is relevant and what is irrelevant, one should run global or regional MHD models with various non-MHD effects. A traditional approach using anomalous transport coefficients (ATCs) has met with mixed success.

Another approach is called flux coupling in which non-MHD effects are conveyed to MHD-scale processes via fluxes in the primitive equations. The equations involve a vector representing the eight primitive MHD variables (velocity, B-field, density, and pressure) and the RHS contains the usual MHD terms as well as non-MHD effects arising from non-ideal terms in Ohm's law, the mass continuity equation (e.g., a mass source), and the pressure and heat flux tensors. Self-consistency may also require appropriate flux coupling terms in the equations defining the non-MHD effects. This raises the question as to whether the form of the (non-MHD) dissipation mechanism is important? The answer appears to be probably not in that steady state but probably so in the transient state. For operational models we should implement engineering fixes now and pursue scientific resolution over the long haul. The detailed nature of localized dissipation is probably irrelevant as long as approximately correct electric fields are produced. Data assimilation is not being done systematically in tail/substorm models at this point. Finally it is evident that we should not ask too much of global MHD.

Transport Model for Ion Weibel Mode

The consensus premise at the moment is that current disruption/reduction is part of the substorm cycle, but there is no agreement on whether it is a cause or effect. In the former case the cross-field current instability must be operative but it requires a relatively large normal magnetic field and cross-field ion flows larger than the ion thermal velocity. The competing model has a dipolarization of the nightside magnetosphere that initiates the event. Here a localized perturbation electric field (e.g. resistive) exists at onset. If initially the motional electric field term is negligible compared with the resistive term, this condition must be violated as time proceeds. Dipolarization occurs in the region earthward of the resistive patch and normal magnetic field reduction tailward. To test the former hypothesis one could imbed Lui's model in a regional or global MHD model to understand its implications in a global context.

Two possible micro-processes that may be responsible for magnetotail current disruption mechanisms are the modified two-stream instability, and the ion Weibel mode. These kinetic processes can provide a means to limit the current density, which might be impossible in MHD. These instabilities operate in thin current sheets, where ions become unmagnetized. The instabilities are presently treated only in local approximations. A possible current disruption scenario is one in which a perpendicular current density becomes partially parallel as the current flows into a region of an enhanced magnetic field, such as is expected in the current disruption region. While no general agreement on substorm onset mechanisms could be achieved, it was agreed, however, that substorm onset and expansion most likely involves more than one process operating simultaneously. The general current disruption mechanism is a simple consequence of Vasyliunas's equation describing field-aligned current generation.

It is important to understand what scale sizes are relevant to magnetospheric dynamics. The large scales, of the order of the dimension of the system, are usually well represented by an MHD description. Other scales, on the other hand, figure most prominently in thin current sheets, where deviations in MHD can become important. The deviations can manifest themselves in one or more additional terms in Ohm's law, leading to a generalized Ohm's law. New effects beyond resistivity to consider here are: electron pressure gradients, Hall effects, and electron inertia. Effects like these can decouple ion and electron dynamics, potentially also involving parallel electric fields and parallel currents at different scales. At scale lengths characteristic of thin current sheets, finite Larmor radius effects also become important.

J. Drake's two-fluid model of reconnection sheds some light on the nonlinear stage of reconnection. Ion-electron decoupling via Hall effects leads to reconnection processes dominated by ions. Electrons form a thin layer with a thickness of the order of the collisionless skin depth, where they become unmagnetized.

Three-Dimensional Features of Magnetic Reconnection

A Harris neutral sheet configuration and a regional kinetic model of the near-earth tail with a dipolar-like magnetic field and attached current sheet have been used to explore 3-D aspects of reconnection. The results of the regional model serve to illustrate the potential importance of 3-D kinetic effects in tail configurational instabilities, but due to the severe computational constraints in implementing kinetic simulations of large volume, inhomogeneous regions, it was noted that it is not clear that the regional simulations map correctly onto actual tail configurations. During solar wind driving, ion-electron decoupling leads to polarization electric fields and embedded thin current sheets. The current in these sheets is carried by the electrons. The thin current sheets are stable (with respect to instabilities with non-vanishing wave vector in the y direction) until reconnection starts. Therefore, the behavior is initially two-dimensional. The north-south magnetic field component readily evolves to a value less than zero, unlike ideal MHD, where such an evolution is prohibited. The three-dimensional evolution generally is much more complicated than in two dimensions. Additional instabilities such as (kinetic and MHD) kink instabilities as well as current sheet breakup effects by whistler dynamics may be important.

Instabilities with wave vectors in the y direction might produce local electron flow velocity enhancements by Hall electric fields. Investigation of such instabilities by 2.5D Hall MHD have produced either nothing (when the current was carried by the electrons) or a Kelvin-Helmholtz instability (when the current was carried by the ions). Using a 2.5D modified hybrid model, strong growth of a lower-hybrid-drift instability was observed on both sides of the current sheet. The interaction between the two sides appeared to lead to a kinking signature in the cross-tail current.

In the future kinetic dissipation should be incorporated into large-scale models. In recognition of the expected difficulties one might start by using simple parametrizations.

Connectivity and Dynamics

A key issue is the coupling of auroral arcs to the tail. Auroral arc structures contain multiple scale sizes from 100 m up to 100 km. and some of this structure maps into the plasma sheet. Auroral arcs must affect plasma sheet properties (e.g., cooling, composition). We do not know what determines auroral arc geometry (long and narrow) and location or what the relationship is between substorm onset, auroral arc formation, and causal mechanism(s) in the plasma sheet. The answer to some of these questions may lie in the presence of resonant Alfvén waves. Salient points, proceeding from larger to smaller scales, include that substorm onset arc maps to the inner edge of the plasma sheet on closed field lines. Field line resonances (Alfvén waves standing on closed field lines between northern and southern ionospheres) are naturally conjugate and are sometimes (usually?) correlated with 10-100 km scale auroral precipitation structures. Locations (L shells) of stimulation are related to natural frequencies of the geomagnetic cavity (so-called global modes). Dispersive properties of kilometer scale Alfvén waves further regulate long and narrow geometry as well as location. Substantial energy accumulates in resonances that form in steep radial Alfvén speed gradients (inner edge of plasma sheet?) and that are unstructured, or weakly structured, in the azimuthal direction (east-west). Parallel electric fields, due to kinetic and electron inertial effects, accompany dispersive Alfvén waves and accelerate electrons and ions, especially at low altitudes. Field amplitudes of dispersive Alfvén waves tend to increase substantially; at low altitudes equatorial magnetospheric signatures may be difficult to recognize. Small-scale (100 m) substructure is a likely result of 1-10 sec time-scale, dispersive resonances excited in the more localized, low-altitude auroral resonator formed by the ionosphere at one end and the relatively steep and highly refractive, field-aligned Alfvén speed gradient that extends up to about 1 Earth radius altitude. Seemingly turbulent structure arising during breakup may be associated with inertial tearing, Kelvin-Helmholtz, and/or fast ionospheric feedback instabilities of auroral arcs.

Magnetotail Plasma Sources

Two major source regions of the magnetotail plasma are the solar wind and the ionosphere. Averaging over losses, the plasma sheet typically requires an ion supply of about 10^{26}/s. The solar wind particle flux, multiplied by the magnetospheric cross section, yields a rate of 3 x 10^{29}/s. Clearly, not all of these particles enter the magnetosphere. The dominant entry mechanisms flow across the magnetopause and diffusion. T. Hill estimates the loading rate of this process as 10^{28}/s. Diffusion, estimated by Hill to lead to a rate of 10^{27}/s $(x/100Re)^{0.5}$. Here x is the effective length in GSM x of the diffusive region.

A comparison of numbers shows that both mechanisms are by themselves sufficient to refill the plasma sheet loss. This does not imply, however, that the ionosphere is irrelevant. While the ionospheric supply rates are presently unknown, the plasma sheet ion population in the inner regions of the plasma sheet can contain up to 50% O+ ions during the recovery phase of substorms. Ionospheric ion supply mechanisms for the plasma sheet are the cleft ion fountain, upward ion acceleration and resistive ionospheric heating. Inclusion of ionospheric plasma sources can constitute an important improvement to global MHD models.

It is possibly relevant to the question of sources that plasma sheet ion density seems to correlate well with the square of the solar wind ion density and that very high plasma sheet densities can be found after sudden increases of Kp following long periods of low Kp values. Direct plasma composition measurements are possible with GEOTAIL, whereas POLAR can observe field-aligned current regions in conjunction with outflow and upward acceleration events.

Coupling

Coupling between the magnetosphere and ionosphere plays a major role in magnetospheric dynamics. In one MHD model, that of J. Raeder, ionospheric conductivity depends on a model of EUV and electron precipitation. The precipitation is modeled on the assumption that particle flux depends on the field-aligned current density, which is taken to be proportional to the field-aligned potential drop. Ionospheric conductivity is found to control magnetospheric convection in the global MHD simulations, as well as substorm occurrence. Ionospheric potential and current patterns can also be compared to observations, such that individual event studies are possible. Further, in this model, region 1 type field-aligned currents usually form inside the open-closed field-line boundary during substorms.

The MHD models are not all the same. For example the Fedder/Lyon model predicted an entirely closed, tadpole-shaped magnetosphere of 165 earth radii length without any tail reconnection under steady northward IMF conditions while Raeder's model predicts the existence of open lobe regions extending beyond 400Re with tail reconnection. Both models, however, show the presence of cusp reconnection, and the associated formation of a low-latitude boundary layer. While no conclusions regarding the source of the differences can presently be reached, they might be due to differences in the numerical models themselves. This question merits further investigation and perhaps a more detailed, inter-model benchmark study. There is presently observational data that is consistent with both models.

Viscous coupling might also be important to solar wind and magnetospheric coupling. About 6% momentum transfer from the magnetosheath is required to explain the tailward flows in the far magnetotail. The Drakou et al. model of the low-latitude boundary layer, which includes viscosity in the ion momentum equation, coupling to the ionosphere, and a hot plasma sheet plasma source, indicates that only 10% of the Bohm diffusion limit is needed to self-consistently explain the observed plasma sheet flows. However, neither the tail current-sheet approximation as employed by Owen and Slavin, nor the thin boundary layer approximation of Drakou et al. are completely satisfactory for describing the apparently thick tailward boundary layer flows observed in the "quiescent" plasma sheet.

A number of key questions of relevance to tail structure, substorm onset, and expansion are as follows. Can MHD model substorm expansion without reconnection? Can nonlocal theories and simulations of current driven instabilities be performed? What is the large-scale system feedback on local instabilities? Can the ionospheric role as a plasma source be included in large-scale models? What are the sources of differences in the Global MHD results and what can be learned from these differences? How can data be assimilated into (predictive) models? What are verifiable and distinguishing data signatures of substorm theories and models?

Mass Exchange with Electrodynamic Coupling Between the Magnetosphere and Ionosphere

Several types of ion outflow have been reported: beams, conics polar wind and the cusp fountain. The former two are greatly enhanced in turbulent fields. Less is known about inflow than outflow. At quiet times the ionosphere supplies about 10% of the magnetospheric plasma but at active times about 50%.

Empirical models for mass outflow rates and energies exist in terms of activity indices, but not in terms of local physical variables such as current density, electric field intensity, density, field-aligned potential drop, etc. This is clearly an area where improvement is needed, in particular for an operational GGCM.

Quantitative Aspects of Global MHD Models

Comparisons have been made between the UCLA model (Raeder) and the Dartmouth/Maryland Model (Lyon, Goodrich). Comparisons to date have involved shock tube results (very accurate comparisons) and magnetopause location (qualitatively correct). Data inputs, grid resolution and model properties are error sources.

The tail's X-point location is determined by the location in neighboring equilibria with the same boundary conditions and the location of thin current sheets. Some predictions of global MHD models include that global configuration depends on local properties like resistivity; that X-lines (and, therefore, reconnection) occurs in the tail most of the time regardless of substorm activity; that loss of global equilibrium leads to substorms; that grad Pe in Ohm's law is important in determining reconnection; and that a single satellite track in the tail is harder to model than ionospheric signatures.

Storm-Substorm Relation

A long-running controversy is the nature of the connection between storms and substorms. While substorms occur at the times of storms, there is no evidence to suggest that substorms cause storms. Rather whatever causes storms seems also to produce substorms. About 90% of the Dst variance can be well predicted from solar wind data alone, without knowledge of substorm indices such as AL. The convective surge model, which claims that Dst (and ring current) enhancements are produced by a sequence of convection surges, does not reproduce the Dst time scales. This was demonstrated via a comparison of concurrent AL and Dst traces. There appears to be no evidence that substorm expansion phase injections feed the Dst index. Some recent studies suggest that a large fraction of the Dst variance might be explained by tail current variations, or the closure of tail currents on the dayside rather that the high-latitude magnetopause. This suggestion might be worth further investigations. In summary, it appears quite unlikely that a storm can be understood as the sum of several substorms, although storms are usually accompanied by substorms.

Connectivity of Magnetopause Merging and the Neutral Sheet

Studies using MHD models to explore magnetospheric connectivity show a new feature at the magnetopause, a wedge-shaped low magnetic field region that extends tailward from the cusp (first pointed out by Siscoe). It forms, with the plasma sheet, a "sigmoid"-shaped structure. Reconnection, plasma heating and entry are found all the way along this region from the dayside into the mid-tail. This model prediction has been verified by means of IMP-8 data, which show very similar magnetic field signatures.

In the presence of an IMF By magnetic field component, the magnetopause essentially appears to look like a vacuum superposition of the geomagnetic and interplanetary field. Reconnection at neutral points is important at the magnetopause. Neutral points are connected by singular lines, the so-called null-null lines. They can also be a site of magnetic reconnection. The neutral point position in controlled by the IMF. Magnetotail reconnection in the presence of a cross-tail magnetic field component involves complicated magnetic topologies, even in the vicinity of the reconnection region itself. This might make the analysis of the magnetic field structure quite difficult.

Dynamics

Global MHD models can also be used to study in higher resolution details of substorm expansion. In an MHD model a substorm is triggered by enhanced magnetopause reconnection. Tail reconnection begins with a slow rate in a localized region. It becomes faster after lobe reconnection, still in a localized region, is initiated. These localized reconnections cause only localized effects, although they include dipolarizations and fast earthward and tailward flows. A substorm is preceded in the simulation by several of these localized reconnection events. It is not entirely clear what causes the localization as well as what determines the locus itself of the reconnection processes. It is quite likely that the IMF direction plays an important role here.

MHD models can be used to study substorm injections by means of particle tracing. Modelers find that substorm electric fields are first enhanced at the X-line. Later, however, electric fields are strongest in the dipolarizing magnetic field region. These electric fields dominate by far the reconnection electric fields. Strong field-aligned currents do not extend all the way into the plasma sheet. They are located on field lines inward of the open-closed field-line boundary. Substorm injections can be understood by energetic particle acceleration in the electric fields associated with the dipolarizing magnetic field. Particle tracing in the MHD fields reproduced the observed dispersion and timing at different local times, ranging from pure ion injections to a combination of ion and electron injections to pure electron injections as one moves from dusk to dawn. The three-dimensional structure of electric and magnetic fields is essential if one wants to explain the distribution functions of injected particles.

Ionospheric signatures of earthward convection associated with reconnection flows prior to their arrival in the inner magnetotail still present a puzzle, and the relation between the local flow channels and the global substorm instability merits further investigation.

5. GLOBAL GEOSPACE CIRCULATION MODEL

5.1 Institutional History

A General Geospace Circulation Model, GGCM, is the ultimate goal of the GEM program. The document of 1988 that laid out the master plan for the GEM program referred to it as a magnetospheric general circulation model, MGCM. But the 1989 GEM report on the workshop on ionospheric signatures of cusp, magnetopause and boundary layer processes generalized the name to its present form. A GGCM was meant to be a geospace analog of an atmospheric general circulation model or GCM. An atmospheric GCM is a numerical code that integrates forward in time the equations of fluid dynamics, thermodynamics and radiative transfer over the whole Earth. It represents continents and oceans parametrically as lower boundary conditions with variable height and with geographically variable coefficients representing momentum transfer (i.e., friction) and humidity transfer. Sub-grid-scale processes, such as cumulus convection, which provides the main source of energy to drive global atmospheric circulation, must be represented parametrically. The solution of the problem parameterizing cumulus convection in GCMs (a.k.a. the cloud parameterization problem) represented a major breakthrough in atmospheric science. Developing a GGCM will entail solving analogous problems in parameterizing sub-grid-scale processes, such as magnetic reconnection.

Atmospheric GCMs are workhorses of atmospheric and climate research. They are also workhorses of operational weather forecasting. They have proven to be powerful and flexible as research tools, which is why the National Center for Atmospheric Research (NCAR) invested millions of dollars and many person years developing a "community climate model," which is a portable GCM for general use by the atmospheric community. The project of creating and updating GCMs for use as community climate models in atmospheric research continues today at NCAR and at other major centers of atmospheric research, such as Goddard Space Flight Center. NCAR's community climate model exemplifies the programmatic niche that a GGCM was meant to fill in magnetospheric science. Since the magnetospheric community has no NCAR, GEM was created to play the institutional role of organizing a community effort to achieve a community GGCM.

As originally conceived, the structure of a GEM General Geospace Circulation Model was to be modular to conform to the modular structure of GEM itself. The idea was that since the goal of GEM was to create a GGCM, the goal of each campaign should be to provide a module for the GGCM. Once all campaigns had been run and interface protocols had been worked out, the accumulated suite of modules could then be fit together to form GEM's finished product, a GGCM. Since on this scheme, model assembly could not occur until all campaigns had been completed, the master plan scheduled a GGCM assembly campaign at the end of the GEM program. After several years of operation, however, the Steering Committee decided that planning for the model assembly should start right away. This decision responded to several concerns. It was felt that the magnitude and difficulty of assembling the model were too great to postpone planning for it until the last campaign ended. A need was perceived to have GGCM interests represented while campaigns were implemented to provide guidance so that campaigns might optimize their results for application to the model assembly. Participants had already begun to generate valuable research tools that could be distributed to the community as stand-alone modules. Perhaps most important, designing the model presented scientific challenges worthy of focus by modelers and likely to produce research leading to publications. Accordingly, the Steering Committee created a working group, the GGCM Assembly Working Group, a.k.a. Working Group 5, to organize sessions at GEM workshops and in general to look after GGCM concerns.

The working group, with J. Fedder (NRL) and G. Siscoe (Boston University) as co-chairs, held its first working group sessions at the 1993 summer GEM workshop. Highlights of these sessions were described in an EOS article, *"Daunting" task of assembling data for a geospace global circulation model begins* [Siscoe and Fedder, 1994]. An issue emerged at this meeting in embryonic form that in a few years would grow into a major change in direction of the GGCM project. For the first time it was suggested that a non-modular version of a GGCM based on global MHD simulation be considered as a alternative to the modular version that had until then seemed the obvious way to proceed. After debate, the participants decided to retain the modular approach to GGCM construction. A large factor in this decision was the perception that a modular approach is inclusive – anyone can participate – whereas an approach based on a global MHD model is exclusive – only one person or group can participate.

To recount the history of GGCM activity within GEM after the inaugural meeting of the Working Group in 1993, it is convenient to treat first its institutional or programmatic history then separately its content or substantive history. The first meeting of the working group made clear to its co-chairs that the construction of a GGCM, like any engineering project, cannot be done in yearly meetings. They decided that, besides the regular meetings at the summer GEM workshop and at the pre-AGU fall meeting, they would hold winter meetings dedicated to GGCM matters. The first winter meeting was held on October 26 and 27, 1993 at Boston College. It continued the themes already defined at the summer meeting, but it introduced space weather as a new theme. T. Eastman, then manager of the Magnetospheric Physics Program at NSF that sponsors GEM activities, challenged the group to develop a prototype model by 1996. It was decided to interpret "prototype" to mean a model that can accomplish some task for the first time. To give more wiggle room in this interpretation, "task" was interpreted to include both scientific tasks and applied tasks. On this interpretation, a GGCM that made a new contribution in the field of space weather would satisfy the Eastman challenge. The legitimacy of a space weather theme for GEM was further bolstered by the creation of the NSF-led National Space Weather Program early the next year. To pursue the space weather theme in the context of GGCM activity, the chairs arranged to hold the 1994 winter meeting at NOAA's Space Environment Laboratory (now the Space Environment Center) in Boulder. The meeting represented the first time magnetospheric researchers met jointly with space weather researchers and service providers to talk about common interests. The meeting was fruitful in identifying candidate prototype models with potential applications to space weather service operations. As importantly, it inaugurated a now annual meeting at SEC of space physicists and space-weather researchers and service providers. The co-chairs again organized the second meeting in the winter of 1995. By the winter of 1996, however, the meeting was deemed of sufficient importance to SEC that, with the concurrence of the co-chairs, SEC assumed responsibility for the meeting and expanded it to include participants from the fields of solar, heliospheric, and ionospheric physics as well as magnetospheric physics. GEM can claim credit for having spawned the now annual SEC space-weather workshops, which have since been codified as "Space Weather Week" at SEC and which also incorporate a users conference.

The most recent SEC meeting (1999) had as its theme "Research to Operations," which was the intent of the Eastman challenge as interpreted by GGCM participants. The first numerical code of a GGCM type that went from research to operation at SEC was the Magnetospheric Specification Model (MSM) developed at Rice University by Dick Wolf and John Freeman, who are GEM participants. It is fair to say that Wolf and Freeman's participation in leadership capacities in GGCM activities and the yearly SEC workshops that GGCM engendered undoubtedly catalyzed the process by which the MSM was finally in 1998 transitioned into operation at SEC. In this sense, the working group can say it met the Eastman challenge, albeit two years too late.

By the summer workshop of 1995, the Steering Committee had "promoted" GGCM activity to a full campaign, not just working group status. The co-chairs were correspondingly elevated to the status of campaign coordinators. The campaign now had three working groups of its own: a Core Working Group led by R. Wolf, a Radiation Belts and Storms Working Group led by M. Hudson, and a Magnetotail/Substorms Working Group led by M. Hesse. These working groups corresponded to an impression at the time of what was known and what still needed to be found out. The Core Working Group would consolidate aspects of the GGCM that seemed relatively well understood – solar-wind-magnetosphere coupling, which set electrodynamic boundary conditions for the volume of the magnetosphere filled with dipolar field lines, and magnetosphere-ionosphere coupling, which determine drifts of particles on dipolar field lines. The Radiation Belts and Storms would add aspects of transport determined by strong inductive electric fields and by stochastic and "mesoscale" electric fields (i.e., electric fields with coherence lengths of a few to about 10 Re and coherence times of 1 to 100 minutes). These kinds of electric fields are primarily responsible for the time-variable parts of the radiation belts and for the ring current, the growth of which characterizes magnetic storms. But they are not part of Core Working Group models, which treat solar wind-magnetosphere coupling and magnetosphere-ionosphere coupling as quasi-static, global processes. The Magnetotail/Substorms Working Group would supply missing physics having to do with reconnection and mesoscale dynamics in the tail, which modulate and condition particles and electric fields that the Core Working Group models take as input parameters. Highlights of the 1995 workshop relevant to the content history of GGCM development are given below.

The summer workshop of 1996 saw a substantial change in the organization of the campaign. The old campaign coordinators rotated off to be replaced by Wolf and Hesse. The two non-core working groups, Radiation Belts/Storms and Magnetotail/Substorms, blossomed into separate, full-fledged campaigns. The campaign focused on research needed to implement a GGCM. To create a management entity responsible for model construction, this steering committee established a standing GGCM Steering Committee, which would function in coordination with the GGCM Campaign. Siscoe was appointed to chair the GGCM Steering Committee. This dual administrative structure for coordinating and managing GGCM research and construction has been maintained to the present. The only modification occurred at the 1999 summer workshop, where to insure coordination between the two GGCM administrative entities, the chair of the GGCM Steering Committee was made a member of the GGCM Campaign organizing committee.

5.2 The GGCM Campaign

Having brought the institutional history of GGCM activities up to the present (July, 1999), we turn to the achievements of these activities. The major themes to this history are the gradual growth in influence of a GGCM structure based on global MHD rather than on modules and the resulting creation of an implementation strategy that would make an MHD GGCM inclusive. This review will follow these themes, ignoring much of interest outside these themes that is also associated with the activities, such as the advent, reviewed above, of space weather as an opportunity for application. Precedence here is given to GEM's main scientific goal, which is to create a powerful research tool for magnetospheric research, a GGCM, and make it widely accessible to the magnetospheric community. This then is a history of progress toward developing it.

As already emphasized, the GEM program founders envisioned a GGCM composed of interacting modules, and they structured the GEM campaigns as engines of research designed to produce the modules. The paradigm that GEM founders used for a modular GGCM was the Rice Convection Model (RCM), developed by a group at Rice University headed by Wolf. The RCM is based on a magnetosphere-ionosphere-coupling model developed by V. Vasyliunas (Max Plank Institute, Lindau-Harz) which has the structure of a feedback loop comprising five interacting modules. Figure 13 shows the coupling between the different processes and regions in this model. The RCM elaborated this pentagonal structure by adding more modules to incorporate more known magnetospheric processes. Around 1990, the RCM was the most powerful physics-based, macroscale numerical code in magnetospheric physics. A conceptual version of it existed containing places for modules of all physical processes that had been identified as playing a role in magnetospheric convection. Some modules were filled with existing codes; others were not owing to missing physics. To build a GGCM was simply a matter of filling in the empty modules by carrying out research needed to find the missing physics. The task seemed to be truly daunting [Siscoe and Fedder, 1994].

Rice Convection Model Logic Diagram

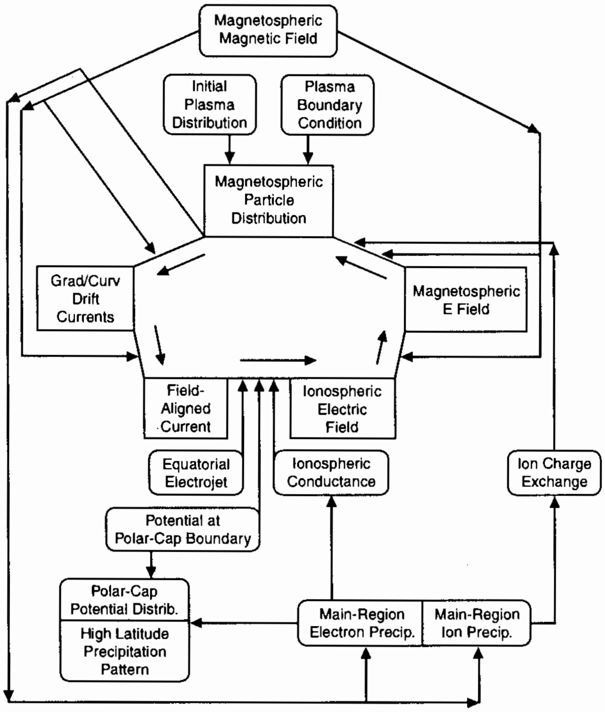

Fig. 13. Function block diagram showing the coupling between different magnetospheric processes in the Rice convection model.

This perception began to be challenged at the 1993 summer workshop that inaugurated the activities of the GGCM Working Group, when Lyon, author of a global MHD code, presented results that simulated a substorm. The power demonstrated here of MHD simulations to provide continuous, global views of dynamical parameters (e.g., electric field) was impressive. One could simulate a substorm without even knowing what a substorm is. Such a feat would seem to be beyond the reach of a modular GGCM, which requires explicit physics for all processes. The workshop summary reporting the sessions for 1993 noted that "global MHD simulations constitute the closest thing to a truly global GGCM that exists." Indeed, a model based on MHD is a close analog to an atmospheric GCM in a magnetospheric setting. It integrates forward in time the equations of magnetohydrodynamics and thermodynamics over the whole magnetosphere. It represents the ionosphere parametrically as a lower boundary condition with variable conductances. Sub-grid-scale processes, such as magnetic reconnection, which enable the transfer of energy from the solar wind to drive global magnetospheric circulation must be represented parametrically, for example by explicit resistance. Nonetheless, after the 1993 workshop, modular thinking continued to prevail among GGCM architects for the seemingly inescapable reason that global MHD simulation codes are big and unportable, which makes them exclusionary. Only a small number of people can participate in research using them.

An area of compromise between RCM and MHD approaches appeared to open at the 1993 workshop. The two approaches complement each other, each being strong where the other is weak. From the perspective of an RCM code, MHD has the advantage of computing self-consistent pressure fields and magnetic fields, whereas an RCM code must use pre-specified, parameterized magnetic field models. As a consequence, an RCM code will never discover something new about magnetic field behavior. From the perspective of an MHD code, RCM has the advantage of computing pressures in the inner magnetosphere where particle-drift transport dominates MHD transport. As a consequence, an MHD code will never brew up a blockbuster magnetic storm. At the 1993 workshop, Wolf conceived the idea of marrying the codes by embedding RCM physics inside a global MHD frame. In iterative fashion, the RCM would compute the pressures correctly and feed them to the MHD code to then compute and return the correct magnetic field. This idea led to two separate GEM projects, mentioned below, where partial success was demonstrated. It has now been implemented and tested in an MHD code being developed for operational space weather applications in the DOD (see below). The GEM GGCM project can take credit for having initiated and fostered this major step in GGCM development, albeit at present not in the GEM context.

The summer workshop of 1994 saw little change from 1993 in the attitude of GGCM architects regarding the general direction of model development. The idea of merging RCM and MHD models took on concrete form in that Dick Wolf and John Lyon pursued it far enough to be able to submit a proposal to NSF/GEM (subsequently funded) to try to implement it. Similarly Birn proposed to join with Wolf in an attempt to merge the RCM with Birn's MHD code that simulates dynamics in the magnetotail, particularly substorms as modeled by rapid reconnection. The merger in this case would have the merit of feeding the RCM magnetic and electric field values generated by a code that has been tailored to represent magnetotail physics realistically.

A sense of reinvigorated GGCM activity pervaded the summer GEM workshop of 1995 when GGCM became an official GEM campaign. Wolf, leader of the Core Working Group, expressed the feeling that, "The business of global magnetospheric modeling has changed dramatically in the last two years – partly because of GEM." As examples he noted that no longer are the same groups doing the same thing year after year, as seen by MHD codes now attacking the inner magnetosphere; global magnetospheric modelers are addressing regional differences in a constructive, collaborative way; and they are making real progress toward a comprehensive model. This year saw the entry onto the GEM scene of two new MHD models: Raeder's parallelized global MHD code and W. White's (Mission Research Corporation, Nashua, NH) Integrated Space Weather Model (ISM). Raeder's code is fast and so well suited for case studies as he demonstrated by showing a comparison (favorable, as it happened) between code output and Geotail data taken 200 Re downtail. MRC's ISM code is the code mentioned earlier that, in collaboration with Wolf's group, has imbedded RCM physics within an MHD frame. White showed results of a run that used the MHD frame alone. Lyon further demonstrated the power of MHD simulations with graphics of a run showing an interplanetary shock wave impacting the magnetosphere. This simulation was made famous by providing the electric field input to a particle drift calculation that successfully modeled a shock-produced, "instantaneous" generation of a radiation belt. Altogether the 1995 summer workshop left the impression of fast forward motion in the area of modeling global magnetospheric dynamics, that is GGCM's area.

The summer workshop of the following year, 1996, when Wolf and Hesse became coordinators for the campaign, marked a watershed at which the enthusiasm felt during the previous year's workshop expressed itself as a strong desire by most, though not universally shared, to begin building a GGCM. During a planning session, a heated debate over whether it was time to start construction was settled decisively in favor of starting. This meant that the architects finally had to face the contentious issue of which type of architecture to adopt. The debate accordingly shifted to this issue, which could not be resolved during the scheduled planning session. Wolf therefore called for a special Town Meeting-style evening session at which formal presentations were made by advocates on both side of the issue, T. Hill arguing for a strict RCM-type model and J. Lyon making the case for an MHD-based model. In summary, a modular approach codifies and therefore directly tests physical understanding. A modular approach has mix-and-match flexibility. A modular approach can be made small enough to run on a workstation. A modular approach allows any researcher to test a theory by developing a module that codifies it then running it as a component of a modular GGCM. On the other side, an MHD approach applies to the magnetosphere a state-of-the-art research tool – computational fluid dynamics – that hundreds of people have worked on, developed, and advanced. An MHD approach brings to magnetospheric physics the heritage of the powerful field of continuum mechanics, which, in the form of geophysical fluid dynamics, has been so conspicuously fruitful throughout other areas of environmental sciences from oceanography to meteorology. An MHD approach provides a close analog to atmospheric GCMs, which are the tried and proven workhorses for research in global atmospheric dynamic and climatology and in the exceptionally demanding and unforgiving field of weather forecasting. An MHD approach requires no assumptions about mesoscale and macroscale physics, so it can discover new things in these realms. At the end of the session, it was clear each side had strong arguments in its favor.

The consensus of the session was to give both options an opportunity to develop its case through the mechanism of a concept study. Wolf put together a committee that drafted a "Plan for the Development of a General Geospace Circulation Model," which recommended that the October 1996 NSF/GEM AO solicit GGCM-development proposals. These proposals would be short-term concept studies that would seek to define the computational architecture of the model as well as the institutional structure to manage community interaction with the GGCM. To implement this recommendation, in May 1997, NSF/GEM awarded three grants. One grant went to Hill to develop a modular GGCM concept; one went to Lyon to develop an MHD GGCM concept; and one went to A. Ronn (TRW Systems and Information Technology, Colorado Springs, CO) to develop a concept of an object-based computational system architecture to allow distributed users access to a GGCM of any type. A GGCM Steering Committee was set up (as described earlier) to assess the merits of the final reports of these studies, which would be due in 1998, and to recommend how to implement the selected concept or concepts.

The debate over the relative merits of modular and MHD GGCMs continued as a major theme in the presentations at the summer GEM workshop of 1997. The concept study grants had just been awarded, so no new results were yet available. By this time, consensus had shifted in favor of an MHD GGCM, but a strong sentiment persisted that both options be implemented. "If only one were possible, however, then make it MHD," seemed to characterize the mood. The consensus reflected the number of groups involved in developing the two types of models. On the modular side, there were two groups: one at Rice University (T. Hill and F. Toffoletto) and one (so far unmentioned but nonetheless making presentations at GEM workshops) split between Lockheed (M. Schulz) and Aerospace (L. Lyons and V. Peroomian). On the MHD side, there were five groups: one split between Dartmouth College and the University of Maryland (J. Lyon, J. Fedder, M. Wiltberger, and C. Goodrich); one at UCLA (J. Raeder, J. Berchem, and R. Walker); one at Los Alamos (J. Birn); one at the University of Michigan (headed by T. Gombosi, who made his first GEM presentation at this 1997 workshop); and one at Mission Research Corporation (W. White, K. Siebert, et al.).

The results of the concept studies were presented at the summer workshop of 1998. Not unexpectedly, advocates of both architectures presented viable concepts. Both would work and both would add importantly to the arsenal available to the magnetospheric researcher. There was nothing here to serve as a discriminator to eliminate one or the other. Instead, there was new enthusiasm for both.

Meanwhile, the Steering Committee, responding to an apparent community mandate to implement at least an MHD model or better both an MHD model and a modular approach, devised a plan to incorporate into the management of such an MHD GGCM the aspect of inclusiveness. Inclusiveness is an aspect that for pragmatic reasons is foreign to MHD code developers, but for an MHD GGCM it is an essential aspect in order to preserve the community spirit of the GEM program. The GGCM Steering Committee's plan also put MHD models and modular approaches on an equal footing. The plan called for implementing development in three phases. In Phase 1, all those wishing their codes to be considered for GGCMs would be made accessible via the Internet and CDs the output of their codes for a suite of runs using as input a set of standard conditions prescribed by the Steering Committee. In Phase 2, all those wishing to participate as suppliers of GGCM services would provide output from their codes on demand by users (with safeguards against abuses, of course). In Phase 3, users would be able to request modifications or to make modifications of the code of any participating GGCM service provider.

The GEM Steering Committee adopted the plan, after which the NSF/GEM AO for 1997 solicited proposals for participants in Phase 1. Three proposals were funded: one from Hill and Toffoletto to provide output from a modular GGCM; one from Raeder to provide output from an MHD GGCM; and one from A. Ridley (Southwest Research Institute) to provide output from an ionosphere-thermosphere GCM developed by R. Roble at NCAR. At the summer GEM workshop of 1999, all three awardees reported that they had completed the runs and that the outputs are available "on the Web." Raeder's website in particular, which contains more than the standardized runs, was being quite heavily used. Following the session at which these results were reported, the GGCM Steering Committee declared Phase 1 of its plan to have succeeded. To improve on the success, however, the Committee perceived a need to advertise the results so that they might be more fully used. To this end, the committee chair would announce the results in the GEM, SPA, and CEDAR newsletters and in an EOS article reporting the success of Phase 1.

Since the three-phase implementation plan for model development was formulated in 1997, a new initiative occurred outside the GEM program that has important implications for implementing Phases 2 and 3 of the GGCM plan. This new initiative is the Community Coordinated Modeling Center (CCMC). The CCMC is a multi-agency initiative that would make available to the space physics community free computing resources for the purpose of developing and testing models that relate to space weather – a criterion for which a GGCM qualifies. Institutionally, the major computing hardware for the CCMC is being provided by the Air Force Weather Agency and is located at the agency's headquarters in Omaha. The front-end system, by which the computing hardware will be accessed is being located at Goddard Space Flight Center, with M. Hesse as its director. At the steering committee meeting held at the 1999 summer workshop, Hesse, who is a member of the steering committee, agreed that the CCMC could perform operational duties of at least Phase 2. The CCMC could provide "runs on demand" as called for in GGCM Phase 2. This would remove the burden from GGCM code providers thereby making it more attractive for code developers to participate in Phase 2. The CCMC can in principle also carry out operational duties associated with Phase 3. But a decision on this should wait until some experience is acquired with CCMC performing operational duties of Phase 2.

A success story completes this July 1999 retrospective of the GGCM project. A significant milestone has been reached in the history of GGCM development, indeed in the history of space physics, because a group of scientists pursued a problem that has from the beginning blocked acceptance by kinetic theorists of MHD results concerning magnetic reconnection. Mentioned earlier in connection with atmospheric GCMs, a significant milestone was reached when atmospheric scientists developed a scientifically correct means for representing sub-grid-scale cumulus convection parametrically in GCM codes. The milestone that has now been reached in GGCM development is analogous to this earlier one reached in GCM development. Over a period of three GEM summer workshops (1997-1999), J. Drake and P. Pritchett led a group of plasma kinetic theorists in a systematic, comprehensive study of the kinetic physics of reconnection. The study was called the "Reconnection Challenge." The challenge was posed and a method to meet it was devised during the 1997 GEM workshop. Between the 1997 and 1998 workshops, each member of the group focused on a specific kinetic mechanism that could cause reconnection. The group presented their findings at the 1998 workshop and made a remarkable discovery: the result is independent of the chosen mechanism. All mechanisms end up giving the same merging rate as that given by Hall MHD. This problem, which has blocked communication between MHD modelers and kinetic theory modelers for over 30 years, is now resolved. It will take some time for the result to work its way into codes but the path is now clear. The Reconnection Challenge Team has been strongly encouraged to broadcast their achievement widely through presentations, papers and articles in high-visibility journals like Science.

In summary, since its inception in 1993, the GGCM project has progressed a great distance, though not in a straight line. Heading first in the direction of a modular approach, it gradually split into streams going in two directions, one still heading toward a modular approach, the other toward an MHD-based model. At present the stream flowing toward an MHD GGCM is larger. To accommodate both streams and to condition the MHD stream to make it satisfy a sine qua non of the GEM program – community accessibility – the steering committee devised a three-phase implementation plan. The first phase of the plan – making model outputs for a set of standard runs available on the web – has now been successfully implemented. A resource to enable phase 2 and possibly Phase 3 of the plan has fortuitously appeared. This is the Community Coordinated Modeling Center, which can take responsibility for operational aspects. Finally, a significant scientific breakthrough has occurred as a result of a study conducted under the GGCM Campaign. It is now established that collisionless reconnection can be treated with the formalism of Hall MHD. All kinetic processes leading to reconnection give the same reconnection rate. The immediate future will be devoted to enlarging the applications of Phase 1 products, celebrating through publications the reconnection breakthrough, and in coordination with the CCMC moving toward implementing Phase 2. Considering that a GGCM was to be the last GEM activity, it is years ahead of schedule and ridiculously under budget. Also at the 1999 summer workshop, the campaign coordinators rotated off to be replaced by Birn and Raeder. It became clear at this workshop that MHD was now a serious contender for adoption as the architecture of choice for GGCM construction.

References

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6. NEAR-TERM STRATEGY

As the GEM program proceeded, sufficient closure ensued in many of the problem areas that were addressed so that it became appropriate to wind down Campaign 1, to begin a new campaign in the inner magnetosphere and to think about other possible future campaigns. It was also noted that the Magnetotail/Substorms Campaign needed a fresh approach. These issues came to the fore in 1997. In the following paragraphs we introduce briefly these issues that will certainly be treated in greater detail in the next GEM report.

6.1 Restructuring of the Magnetotail/ Substorms Campaign

The Magnetotail/Substorms Campaign has the broad goal of understanding the dynamics of the tail and its relationship to geomagnetic disturbances. As this campaign progressed, it became apparent that there are a variety of different types of disturbances that involve different aspects of tail dynamics. In addition, the full complement of NASA ISTP spacecraft became available and capabilities for ground observations of ionospheric manifestations of disturbance phenomena dramatically improved. This greatly added to our ability to observe the tail and its relationship to the solar wind and to geomagnetic disturbances. To take advantage of our developing knowledge and of the new observational opportunities and to satisfy the evolving needs of the community, the Magnetotail/Substorms Campaign was restructured in 1997. It was decided that the campaign should be divided into three new working groups and that their activities and their interactions with other active GEM campaigns should be coordinated by a campaign coordinator. L. Lyons, who had been involved with this campaign from its inception, agreed to become campaign convener. The three working groups included an Observations Working Group (co-chaired by M. Moldwin and S. Ohtani) with the ambitious goal of developing a model-independent phenomenological description of substorms that models should be able to explain. Another working group on Quantitative Magnetotail and Substorm Models was to be chaired by J. Drake and J. Lyon. This working group is to cover both the steady-state aspects of tail dynamics and the temporal evolution associated with different disturbances. It was furthermore felt that models had become sufficiently sophisticated that a dynamical tail event with comprehensive data coverage should be selected as a "Challenge" to modelers. N. Maynard and J. Raeder agreed to coordinate the selection of an event, as well as the observational and modeling activities for this challenge to the modelers. In addition, observational studies of non-substorm disturbances during conditions of prolonged enhanced convection (i.e., magnetic storms, steady magnetospheric convection periods) are to be coordinated with other GEM campaigns.

6.2 Inner Magnetosphere and Storms Campaign

The goals for the Inner Magnetosphere and Storms (IM/S) Campaign were defined by three working groups that met at the annual GEM Snowmass Meeting in June 1996 and 1997. These and their co-chairs were:

- Working Group 1: Plasmasphere and ring current coupling, J. Horwitz and J. Kozyra, co-chairs
- Working Group 2: Storm injection and recovery mechanisms - ring current and radiation belts, D. Baker and M. Hudson, co-chairs
- Working Group 3: Energetic electron variability, R. Thorne and G. Reeves, co-chairs

Each working group posed a set of questions, which constituted a starting point for the new campaign, to be augmented by further community input. It was further decided at the June 1997 meeting to reduce the number of working groups from three to two, incorporating the ring current issues into the activities of WG1 and radiation belt issues into WG2. Mary Hudson stayed on as campaign coordinator for 1998 and 1999, with Horwitz and Kozyra chairing WG1 (Plasmasphere and Ring Current) and Reeves and Thorne chairing renamed WG2 (Radiation Belts). Appendix B presents the Strategic Plan for the campaign that was drafted in spreadsheet form listing the key unanswered questions, the needed knowledge and tools as well as the suggested strategies.

The IM/S Campaign was recognized as a full initiative for funding consideration in the 1998 GEM AO. At the 1999 Snowmass meeting, IM/S Campaign working groups met for the first time jointly with the 1) MI Coupling WG, 2) Magnetotail/Substorms and 3) GGCM splinters. In addition IM/S WG1 and WG2 met jointly as well as separately to discuss common issues. Three storm periods were identified for study jointly with Cedar and Shine: 14-17 May 1997, 24-27 September 1998 and 18-23 October 1998. Data and modeling presentations for these events were the focus of WG1 and WG2 sessions at Snowmass, as well as a joint Cedar-GEM-Shine day at the Cedar meeting in Boulder on June 18, 1999. D. Baker, M. Hudson and D. Knipp participated in the Cedar-GEM-Shine Killer Electron Workshop in Boulder on June 19, 1999. Tutorials were given at the 1999 GEM Snowmass meeting by A. Korth (ring current observations) and A. Chan (radiation belt models). A. Chan was appointed IM/S Campaign coordinator by the GEM Steering Committee for the remainder of the campaign. The efforts of the working group were split into four areas: coordination with CEDAR and SHINE storm studies, studies of the ring current and plasmasphere, studies of the radiation belts, and coordination with the GGCM effort. The following paragraphs summarize these efforts to date.

Joint Activities with CEDAR and SHINE

Joint activities with CEDAR and SHINE communities, both at the 1999 CEDAR and SHINE Meetings in Boulder, and at the 1999 GEM Snowmass meeting, were preceded by establishing GEM Storms web pages at http://leadbelly.lanl.gov/GEM_Storms/GEMstorms.html. A copy of this website has also been archived on the CD-ROM that accompanies this report.

These pages are designed to be a clearinghouse for exchange of data, plots, ideas, and analysis for the GEM Inner Magnetosphere/Storms Campaign.

Three recent storms were selected by GEM in consultation with the SHINE and CEDAR communities for intensive study. The objective of the campaign is not to analyze the storms independently but rather to intercompare the three storms. The storms were selected based on the following criteria:

- A halo CME observed by the SOHO LASCO experiment that appeared to be aimed earthward
- A magnetic flux rope signature detected by WIND and/or ACE 3-5 days later
- A major (Dst <-100 nT) geomagnetic storm triggered
- A reasonably complete data set for the event. To meet this criteria, events were selected: 1) with as complete as possible information on the solar source regions, 2) with uninterrupted ACE and/or WIND coverage, 3) after the launch of the POLAR spacecraft to provide as complete as possible magnetospheric coverage and 4) during incoherent scatter world days.

The selected storms are:

15 May 1997, 25 September 1998, and 19 October 1998

In addition these pages collect information about several other storms that are not specifically part of the GEM-IM Campaign but are being actively studied by members of the community. They are:

2-4 May 1998, 10 March 1998, 26 June 1998, and 26 August 1998.

Data sets include LANL energetic particles, 5-min AE and Dst indices, South Pole ASC, Millstone Hill Radar, HEO summary plots, and others. Specific event intervals are posted on the website.

Working Group 1: Ring Current and Plasmasphere

Two key areas of new input to plasmasphere-ring-current modeling include improved electric field measurements, beginning with CRRES and now POLAR measurements, which show strong electric fields penetrating into L=2.2 during the main phase of storms (Wygant, 1998 GEM Tutorial; Ober, 1999 WG1 splinter session). Secondly, ENA (neutral) imaging has been obtained from POLAR for recent storms, and will be available for the campaign at higher resolution with the launch of IMAGE in 2000. Dst remains a standard indicator of ring current development, however, new mapping techniques which incorporate ring current asymmetry were presented (Clauer) along with statistical correlations with upstream solar wind parameters. For example, solar wind density has been shown to correlate directly with plasma sheet density and subsequent magnitude of ring current response (Borovsky and Thomsen). Modeling ring current evolution for the September 98 storm shows that the bulk of the main phase ring current for major storms is on open drift paths, and that drift to the magnetopause is a major loss mechanism for storms with a strongly compressed magnetopause (Liemohn).

Working Group 2: Radiation Belts

With the first full year of funding complete, the Radiation Belt Working Group formulated two principal objectives for the next stage of the campaign:

1) To evaluate the relative contribution of various proposed acceleration processes through theory, modeling, and comparison with data

2) To create time-dependent phase space density profiles of the radiation belts that will more accurately represent their structure and dynamics than fixed-energy profiles.

Theory and models of relativistic electron acceleration were identified:

1) Radial diffusion explains quiet periods well, e.g. summer 1996.

2) Salammbo (Bourdarie), a Fokker-Planck code, is the best-developed model for changes in the radiation belt fluxes on daytime scales. It reproduces the gross features of radiation belt evolution using a prescribed diffusion coefficient with no explicit solar wind input. It needs geosynchronous boundary conditions over a broad range of energies, plasmapause location and wave intensities. It does not currently include the adiabatic "Dst" effect. Salammbo could be improved with knowledge of time-dependent diffusion coefficients and plasmapause wave intensities.

3) Shock acceleration was clearly effective in some storms such as March 1991 (Li). General contribution to other events is unknown. If it contributes, then how much and how often? If it does not act alone, then what other processes contribute?

4) Substorm Contributions - What is the contribution of particles injected in substorms? Do substorms provide a "seed population" or are they sufficient themselves? Simulations show a 20 keV particle at 20 Re can become 900 keV at 6.6 Re. Need to know Ey across the magnetotail, plasma sheet density, and electron temperature.

5) Drift Resonance - Good success by Dartmouth group using wave fields from global MHD simulations. Toroidal oscillations with radial electric field resonate with particle drifts. Azimuthal electric fields may contribute to enhanced radial transport. Pc5 waves with enhanced amplitudes are observed in geosynchronous particles and fields, as well as ground magnetometers, correlated with relativistic electron events. Ground magnetometers show strong correlation between Pc5 and Vsw. Multi-storm comparison not yet complete.

6) VLF Whistler Resonance - Several possible contributions:

a) resonance with substorm-associated chorus that randomly changes magnetic moment and energy
b) resonance with plasmaspheric hiss and EMIC waves responsible for "local recirculation" and acceleration

Some are results already incorporated in Salammbo.

Development of Phase Space Density Maps: Questions They Will Address

1) "Removes" adiabatic responses such as the "Dst effect".

2) This is required to know when and where acceleration is taking place (e.g. non-adiabatic in at least one of the invariants).

3) Phase space density as a function of the three drift invariants and time requires time-dependent storm-time magnetic-field models to

calculate invariants;

4) Need to do spectral fitting and/or extrapolation for detectors with finite energy bands.

5) Need to know time evolution of the pitch angle distributions.

6) Both single-spacecraft and multi-spacecraft studies can contribute to better understanding of particle dynamics and global magnetic field models.

7) What solar wind parameters control the structure and dynamics of the radiation belts and what are the relative contribution of external (solar wind) vs. internal (waves, ring current, etc.) processes?

8) Does the pre-existing condition of the inner magnetosphere and/or plasma sheet affect radiation belt enhancements?

9) What are the relative roles of "losses" compared to "redistribution"?

10) To what extent does loss into the atmosphere affect the global electrodynamics and/or chemistry?

11) How important are azimuthal asymmetries in the ring current and radiation belt particle drifts?

Relationship to GGCM

A ring current module is needed for feedback to the GGCM, since global MHD simulations include pressure increase during storm main phase, but do not accurately characterize the recovery phase which depends on single particle drifts and loss rates via collisions and wave-particle interactions.

The radiation belt module will probably not feed back information to the spine of the GGCM because mass, current, and energy densities are too low. Depending on the amount of information needed from the spine the radiation belt module could run separately from the spine or may need be embedded. Although no direct two-way exchange of information is envisioned, the radiation belt module could provide important tests and verification of the GGCM by means of information such as the intensity of wave fields or consistency of particle drifts with magnetic field configurations.

While the IM/S planning document outlines outstanding questions to be addressed by the campaign in more detail, four science questions for focus in studying the storm periods identified with Cedar and Shine communities were formulated in a wrap-up session at the 1999 Snowmass meeting:

1) How is energy transferred from the solar wind into the ring current?

2) What are the relative contributions of the ionosphere and solar wind to the ring current?

3) What are the mechanisms for accelerating MeV electrons?

4) How does previous history affect ring current and radiation belt evolution during storms?

Future working group sessions will focus on specific science issues, and GEM challenges will be identified, for example, a quantitative comparison of the different models now proposed for relativistic electron acceleration for a particular storm period.

6.3 Future Strategy: Magnetosphere-Ionosphere Coupling

In the initial campaigns of the GEM program, the ionosphere was often regarded as a viewing screen on which scientists could study the larger-scale evolution of magnetospheric processes. Electric fields, currents, and energetic particles generated by various solar-wind/magnetosphere interactions could be studied through their ionospheric images. These images, which include ionospheric electric field and convection patterns, horizontal current patterns and auroral luminosity patterns, are representations of the two-dimensional evolution of magnetospheric configuration and they help scientists to understand the mesoscale and macroscale evolution of the large and complex plasma system that surrounds the Earth. As our understanding of the complexity of the geospace environment has evolved, we have begun to realize that the ionosphere plays a far greater role in the onset and evolution of magnetospheric processes than we had heretofore appreciated. First, the ionosphere is a conducting boundary that closes the currents generated by magnetospheric processes. Particle precipitation causes the localized conductance of this boundary to be highly structured and variable, resulting in highly variable current closure and some degree of ionospheric control on magnetospheric processes. Second, ionospheric ions have been found in significant abundance in the magnetosphere, particularly during disturbed periods when there is rapid energy transfer between the ionosphere and magnetosphere. The ions are heavier than solar-wind-derived ions and can moderate the nature of magnetospheric processes. Third, the ionospheric plasma transfers energy and momentum into the neutral atmosphere and can recover some of this energy and momentum from the atmosphere when the solar-wind/magnetosphere interaction is reduced. At these times, the atmosphere may become the driver of some magnetospheric processes.

In response to this growing appreciation of the importance of MI coupling, a working group was formed to identify topics of perceived importance to GEM objectives and to highlight these topics at GEM meetings in 1998 and 1999. Two topics have repeatedly been found to be of very high importance. These are the impact of spatial and temporal variability of ionospheric conductance on mesoscale and macroscale magnetospheric processes and the impact of transported ionospheric ions on magnetospheric processes. Discussions at the 1999 GEM meeting have centered on how well critical issues associated with these topics have been incorporated into various models that comprise the GGCM. The MI Coupling Working Group currently plans to use the 2000 GEM meeting as a planning session to develop a detailed campaign proposal for presentation to the GEM Steering Committee and the GEM community. It is envisioned that the activities incorporated into this campaign will complement those in the Inner Magnetosphere and Storms Campaign and the GGCM modeling effort. It is also anticipated that some of the activities currently carried out within the Magnetotail/Substorms Campaign will be completed under the auspices of a future MI Coupling Campaign.

7. GROUND-BASED PROGRAM

Ground-based observations are an extremely important component of magnetospheric physics as they provide the only means we have currently of observing the magnetosphere/ionosphere system globally or over significant spatial scales. With the very important exception of remote sensing of auroral emissions, spacecraft provide in-situ observations only from their current location in their orbit and so are incapable of monitoring global dynamics except in statistical ways. As the overarching goal of the GEM Program is a GGCM describing the global dynamics of the magnetosphere, global observations of magnetospheric dynamics must be an integral part of the overall program.

The NSF provides the primary support for ground-based observations relevant to magnetospheric physics in the US, through both the Upper Atmosphere Section and, for high-latitude observations, the Office of Polar Programs. While the GEM Program itself has provided only modest support for ground-based observations, the primary beneficiary being the establishing of a new high-latitude network of magnetometers, MACCS, in the Canadian arctic between the existing CANOPUS and Greenland networks, it was natural for the GEM Workshop to evolve into a primary forum for established ground-based observers. Through judicious invitations many of the leading European ground-based observing groups began attending the GEM Workshop, thus providing the critical mass of scientists and observations needed to obtain global images of the magnetosphere from ground-based data. An example of this is Working Group 3 on Current Systems and Mapping of the Boundary Layer Campaign. This working group brought together not only most of the scientists working on the large dynamic transients known as TCV's (travelling convection vortices) but also most of the relevant observations too. By combining European and Northern American data a complete global picture of this phenomenon was obtained for the first time and, as a result, substantial progress was made in understanding its global nature.

The GEM Program has provided a forum where ground-based observations can be discussed and not be overshadowed by the much more glamorous and well-endowed spacecraft programs, which has led to a rerecognition of the value of ground-based observations and has helped substantially in the revitalization of the field.

8. EDUCATIONAL COMPONENT

While the GEM Program does not have a formal educational component, its annual workshop has come to be seen as an excellent way to introduce and bring students, especially graduate students, into the field. Students learn much more at a relatively small, focused, and informal meeting such as the GEM workshop, where there is a much opportunity for discussion and debate, than they do at a large national meeting such as the AGU meeting. From the start of the GEM Program funds have been earmarked for supporting students to attend the annual workshop. As the workshop attendance has grown, so has student numbers, so that student participation has remained at 20-25% of the total workshop attendance. Students who have come to a GEM Workshop invariably request to come in future years and speak highly of the small, relatively informal sessions where they feel freer to participate and ask questions.

Following the 1996 workshop, two then graduate students, A. Ridley (U. Michigan) and K. Hirsch (Boston U.), requested permission (and space) to hold a student organized tutorial session on the day prior to the Workshop. They felt that the regular Workshop tutorials, aimed primarily at established researchers, assumed more background than many students had and that students would benefit from a set of more introductory tutorials intended for students. In keeping with the grass roots style of the GEM program, this student-run program has prospered.

Each Sunday before the start of the main workshop the students organize their own program where the more senior students present a coherent set of tutorials covering the topics to be addressed at the meeting to the students attending the workshop. The students request that this tutorial session be open only to students and be run entirely by students has been respected, as the students feel less restricted to ask and answer questions in an environment where their faculty supervisors are not present and hence learn more.

9. CONCLUSIONS

1997 brought an end to the first GEM campaign, the Boundary Layer Campaign. It also brought the General Geospace Circulation Model into prime focus, restructured the Magnetosheath/Substorms Campaign and nurtured the beginnings of the third GEM Campaign on the Inner Magnetosphere and Storms. The campaign's end both celebrated the program's first successes (and it was very successful) and recognized the diversity of problems that are still to be faced. With limited budgets and a limited number of people, we must focus on finite problem areas in order to bring to bear the critical mass of talent required to solve problems. The GEM campaign's approach to science has optimized the science return within the limited resources of the NSF's effort in magnetospheric physics. It has served as an excellent test bed of focused problem solving and provided a model for the future conduct of the program.

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Geospace Environment Modeling (GEM) Workshop Strategies for the Tail and Substorm Campaign

July, 1993

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Appendix B. Strategic Plan for the Inner Magnetosphere and Storms Campaign

4 Year Inner Magnetosphere and Storms Campaign - 1st Draft Strategy

Key Unanswered Questions	**Needed Knowledge/ Modeling Tools**	**Suggested Strategies**
Global Issues		
How do the highly structured and temporarily varying electric fields in the inner magnetosphere impact ring current development, thermal plasma heating and structuring, radiation belt dynamics and overall magnetic storm development?	• Need physical models of the electrodynamics of the IM driven by (and tested against) data to explore how the large-scale E field is established. • Need parameterized semi-empirical models that have been tested against physical models and data.	*Data Analysis*: • Studies using particles as tracers • Studies of the temporally-varying potentials derived from ENA maps • Studies of patterns derived by mapping of observed ionospheric E fields • Studies of CRRES electric field data in the IM • Comparison with plasma flow measured at geosynchronous orbit *Modeling Studies* • Comparison of RCM runs with data • Parameterized electric field model development & testing • Event studies and test runs of other physical models with all available electric field models & comparison with data
What are the key elements that distinguish storms (e.g., solar max versus solar min, CME vs. high-speed-stream driven, severe vs. minor in intensity)? How do preconditioning and initial state (non-linearity effects) figure into this?	Improved representations of electric and magnetic fields, the low-altitude portion of the geocorona, composition, density & temperature variations in IM plasma source populations, etc.	• Comparison of carefully selected event studies representative of these types of storm events. • Statistical studies • Parametric modeling studies.
What are the details of the global energy balance during storms? What portion of the energy is available to the IM? What is the nature of the coupling between storms and substorms? How does the energy balance vary among storms with different characteristics, different drivers, etc.?	Better understanding of • the physical meaning of the Dst index and local time asymmetries in the disturbance magnetic field • how effective are predictive functions based on upstream solar wind conditions at representing the true energy balance?	• Comparative event studies (same as above) • MHD model estimates of the energy input for selected solar wind conditions or events • Comparison of outputs of physical models with predictive functions based on upstream solar wind inputs.

4 Year Inner Magnetosphere and Storms Campaign - 1st Draft Strategy		
Key Unanswered Questions	**Needed Knowledge/ Modeling Tools**	**Suggested Strategies**
Global Issues (cont'd)		
How does the composition of IM source populations and the variability in this composition impact the storm development and recovery?	How do we define and model in a time-dependent fashion: • SW, ionospheric, & plasmaspheric (?) sources for the near-Earth plasma sheet? • ionospheric plasma directly injected into the IM? • direct effects on the IM of the auroral zone when it moves to low L during storms?	• Coordinate activities in this area with the Magnetosphere-Ionosphere Coupling Campaign • Model the temporal changes in the composition of the inner plasma sheet using a parameterized ionospheric outflow lower BC (based on DE data) as input to a two-fluid (H^+ and O^+) MHD model. Use as outer BC for IM models • Further statistical and event studies of s/c observations (particularly useful would be analysis of low energy ion data from CRRES, POLAR, FREJA, AKEBONO for evidence of ionospheric injections directly into the IM)
Ring Current Issues		
What are the important ring current formation and loss processes? How do they vary between storms with different characteristics? What is the contribution of the electron ring current?	Modeling & investigation • non-adiabatic effects on RC particles due to B field distortions • Wave-particle interactions • effects of compressions • quantifying & understanding precipitation losses • understanding mechanisms that produce variations in the source population • better electric and magnetic field models	• ENA measurements to follow global decay for selected events. • Statistical studies and event analysis of IM precipitation during storms • RC model tests of proposed convection field models, convection + induction field models • Event studies of WPI where detailed wave and particle distributions are available • Statistical studies of wave observations in the IM • Observational studies of ion losses at the magnetopause (esp., during compressions) • Event and statistical studies investigating the impacts of variations in the source population

4 Year Inner Magnetosphere and Storms Campaign - 1st Draft Strategy		
Key Unanswered Questions	**Needed Knowledge/ Modeling Tools**	**Suggested Strategies**
Radiation Belt Issues		
What are the sources, losses, acceleration and energization mechanisms that are responsible for the build-up and decay of the radiation belts? What are the solar wind drivers?	Need to identify • source populations and their origins • waves responsible for diffusion • temporal variations in the diffusion coefficients (D_{LL}, $D_{\alpha\alpha}$, D_{EE}, etc.) • effects of magnetopause losses Need better electric and magnetic field models, thermal plasma models	*Observational tests of specific theories* • Statistical studies of waves during RB formation • Studies of RB pitch angle distributions to test acceleration theories • Statistical studies to identify source distributions using space phase density • Observational studies of losses at compressed magnetopause (statistical and event) • Ion composition/charge state studies to investigate entry of SW or ionospheric ions • Event studies involving the measurement and modeling of the plasmapause profile relative to the RB location (possible unappreciated coupling)
Thermal Plasma Issues		
How do electrodynamic and energetic processes, operating on the thermal plasma in the IM, produce the observed structuring in temperature and density? ... how does this structuring impact coupling processes to the higher energy plasma? ... how does it impact storm development? ... the non-linearity of storms? ... what is the role of superthermal distributions in redistributing energy?	Need to understand (1) erosion, (2) drainage plumes, (3) where plasmaspheric plasma goes after encountering the magnetopause, (4) impact of thermal temperature and structure on wave generation, propagation and damping, (5) transfer of energy from the RC to the thermal plasma and its variability, (6) effects of SAIDs, (7) how superthermal distributions move energy through the system, etc.	• GPS observations to define the temporal behavior of the thermal plasma for selected events • ULF ground observations combined with other data to track the thermal plasma structure (due to erosion, refilling, substorm fields, ionospheric electric fields, etc.) during selected storm events • Coordinated campaigns involving multiple s/c & ULF studies of plasmaspheric structure combined with ground-based observations of the ionospheric electric field and models • Event studies to examine the coupling between the thermal structure and RC/RB dynamics

Inner Magnetosphere and Storms Campaign
Overview of 4 Year Strategy

Time Interval	**Parallel Strategy Components**	
	Major Storm Studies	**Smaller Event Studies, Statistical Studies Development of Parameterized Models**
Beginning Year 1	• Comparative study of 2 magnetic storms triggered by different SW drivers (CME vs. high-speed stream). • Candidate events will be displayed on web site & e-mailed to community. • Request that comments on satellite and ground based data availability, solar wind drivers, other interesting aspects be sent to Geoff Reeves. Also other storm suggestions • Selection of events by Fall AGU meeting. • Candidate events include: 25-29 Aug 1990 4-5 June 1991 7-10 July 1991 15-18 May 1997 17-18 Feb 1998 2-10 May 1998 • Send out query to GEM community with the detailed strategy document & details of events selected • Solicit participation of the Storm Event campaign • Start a web site housing data and model outputs from the storm study	• Send out query to GEM community with the detailed strategy document • Solicit participation of core efforts from each participant • Request descriptions of core efforts from each participant • Table of participants and their interests will be listed and continuously updated on a web site for the community • In addition, participants will be actively recruited to fill gaps in the strategy, and/or supply crucial models, data sets of boundary conditions. • These studies will be carried out throughout the 4 year campaign • Anticipate special GEM sessions and debates and paper sets to result from these small scale but crucial studies.
Subsequent Years	Phase in other comparative storm studies as appropriate. Would like to examine solar max vs. solar min, small vs. intense, single-dip vs. double-dip, etc.	• Strong input to, & collaboration with, larger storm studies due to continuous improvements in understanding and modeling of important physical processes. • New gaps may be identified by major storm studies and added to strategy

Appendix C -Bibliography: Gem Boundary Layer Campaign, 1990-1998

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