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Contract/Grant No.:	NAG5-4771
Project Name:	"Coupling of the Inner Magnetosphere with the Underlying Atmosphere and Ionosphere"
Report Author(s):	Janet Kozyra
Report Preparation Date:	6/13/2005
Report Type:	Final Technical Report
Period Covered:	5/1/1998-4/30/2001
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The following is a final report summarizing our very successful inner magnetosphere research program through which we have made significant contributions to: (1) research through data analysis, modeling and participation in community-wide campaigns, (2) the development of the space science discipline through leadership in national and international campaigns, service on steering committees, review panels and the development and maintenance of campaign and community web sites , (3) education and human resources by the participation of graduate, undergraduate and high school students in our research programs and (4) outreach through development of web-based materials and interactive games. We describe each of these activities below.

Research Program

Over the last 3 years (1997-2000) our research program has been focused on investigating the global energetics of magnetic storms, including energy transport into and through the inner magnetosphere and its transfer into the underlying atmosphere and ionosphere through particle and heat fluxes. Since we emphasize the energetics and dynamics of the inner magnetosphere and coupled regions, we have avoided modeling difficulties in the stretched magnetotail and have limited uncertainties in the energy inflow by using an observed outer boundary condition near geosynchronous orbit. The main assumption here is that all acceleration processes associated with tail dynamics during magnetic storms have already taken place prior to the arrival of these populations at geosynchronous orbit. Conditions at geosynchronous orbit are representative of the injection boundary of Mauk and McIlwain. The LANL geosynchronous satellites and other missions through the inner magnetosphere (e.g., CRRES and AMPTE/CCE) monitor the plasma conditions at this outer boundary during a magnetic storm. The DMSP satellites in low Earth orbit provides information on the electron auroral boundaries which are used to infer the details of the magnetospheric electric field and related convection velocities [Gussenhoven et al., 1981; Burke et al., 1998; Korth et al., 1999]. The combination of these two quantities specifies the energy inflow into the inner magnetosphere. Changes in the outer boundary energy inflow in response to magnetic storm conditions are observed directly and their impacts on the inner magnetosphere, Dst index, current systems and coupling to underlying regions are modeled and compared to observations. The independently measured energy inflow is compared to statistically derived energy input functions based on upstream solar wind conditions to see which functions best describe coupling of the solar wind energy into the ring current region. Observations of precipitating ions from the NOAA satellites and of elevated ionospheric electron temperatures from subauroral radars (e.g. Millstone Hill) allow a more realistic specification of ring current losses and loss lifetimes. We use this information to investigate the geo-effectiveness of solar wind transients, defined as their ability to produce large ring currents or divert large amounts of energy into the inner magnetosphere and underlying subauroral and midlatitude atmosphere and ionosphere. These techniques are a powerful means of investigating the physics of magnetic storms. Major accomplishments for the last grant period are listed below.

Major Science Accomplishments

- Ion precipitation and losses of ring current ions at the compressed dayside magnetopause [Kozyra et al., 1998a] contribute significantly to the fast time-scale recovery of the ring current during the major magnetic storm of February 1986. This raises the questions of whether the ultimate strength the ring current can be limited by losses at the magnetopause during intervals of high solar wind dynamic pressure and under what conditions precipitation losses are important to the global time-scale for decay.
- Enhancements in density and temperature in the near-Earth plasma sheet during magnetically active periods have a dramatic impact on the intensity of the storm-time ring current [Kozyra et al., 1998a] that ultimately forms. An increase in plasma sheet density during the main phase of the November 1993 magnetic storm was responsible for a factor of 3 enhancement in the ring current intensity and was reflected clearly in the Dst index. These density and temperature enhancements are strongly correlated with upstream solar wind density and velocity, respectively [Borovsky et al., 1998] providing a means of driving ring current models solely with knowledge of solar wind conditions upstream from the Earth.
- Some rapid partial recoveries [Kozyra et al., 1998c] of the ring current can be related to changes in the energy inflow from the nightside inner plasma sheet rather than to collisional or wave losses of trapped ring current ions. During the November 1993 magnetic storm, the Michigan RAM model reproduced one partial ring current recovery in the absence of collisional losses and related this recovery directly to a decrease in the nightside plasma sheet density followed closely by a decrease in the convection electric field.
- The contribution of ion cyclotron waves to the ring current recovery during the November 1993 magnetic storm was estimated using the RAM model to describe the evolution of pitch angle anisotropies and densities in the ring current protons [Kozyra et al., 1997a]. These proton characteristics were used to identify time-dependent regions of wave instability in the model. Within these regions, diffusion coefficients of reasonable amplitude were introduced to scatter resonating ions in pitch angle during their drift through the unstable regions. This technique was an extension of that developed by Jordanova et al. [1997]. Small but significant contributions to the Dst recovery during the storm were produced by resonance of oxygen ions with ion cyclotron waves in these unstable regions.
- Observations of plasma sheet ion populations and electron auroral boundaries has allowed an accurate determination of the energy inflow into the inner magnetosphere during magnetic storm conditions [Kozyra et al., 1998b]. A comparison of this observed energy inflow with statistical energy input functions based on upstream solar wind parameters indicates that the Burton et al. [1975] energy input function most closely approximates the observed values. The epsilon parameter seriously overestimates the energy input to the inner magnetosphere but better describes the total energy input to the entire magnetosphere. Global energy loss time-scales have been significantly overestimated in magnetic storm-time energy balance calculations. For the November 1993 magnetic storm, the ring current comprised only 15% of the

total magnetic storm energy budget (estimated using the AMIE model along with RAM model outputs for the ring current), calling into question the practice of using Dst to define the geo-effectiveness of solar wind structures. We are building up a statistical data base by calculating the global energy budget for a wide variety of magnetic storms (see description of future proposed work).

- We have made some initial progress in addressing the question of the impact of preconditioning the magnetosphere on the geo-effectiveness of a solar wind transient event. There is evidence [Kozyra et al., 1998b] to suggest that inner plasma sheet density variations play an important role in determining the ring current strength during storms with two intensifications. These storms are triggered by complex solar wind structures containing two intervals of southward Bz. They are called double-dip Dst storms and are thought to produce some of the most intense events. During the October 1995 magnetic storm associated with the passage of a magnetic cloud with two intervals of southward Bz, some process in the first interval apparently preconditioned the magnetosphere so that denser plasma convected in from the magnetotail during the second interval of southward Bz. As a result, the second interval of southward Bz was much more geo-effective. Comparable ring current intensities were achieved in the two intervals despite the weaker convection electric field in the second interval.
- The dominant loss of ring current ions during the main phase of large magnetic storms occurs due to ion drifts out of the dayside magnetopause. The bulk of the ring current is not trapped but makes one pass through the inner magnetosphere before it is lost. This is the reason why the ring current has been observed to be very asymmetric during the main phase of large storms. The presence of a major partial ring current component in the main phase has implications for the interpretation of the Dst index, storm-time current systems and ground-based magnetometer maps. During the late recovery phase, the ring current finally becomes symmetric, nondivergent and charge exchange loss of ring current ions dominates all other erosion processes [Liemohn, et al., 1999].
- The influence of the ring current on plasmaspheric refilling was investigated in a number of studies. It was determined that the early stages of plasmaspheric refilling are not greatly influenced by the presence of enhanced hot populations near the equatorial plane [Liemohn et al., 1999a], and that in fact the low-energy ion density near the equator actually increases because they are slowed down (but not repelled) by a small electrostatic barrier set up by the ring current ions [Liemohn et al., 2000]. It was also determined that the ring current can supply a significant number of low-energy ions to the outer plasmasphere through charge exchange (the by-product cold ion), and that these particles can act as a catalytic seed population to boost the thermal plasma density high enough to begin the final collision-driven stage of plasmaspheric refilling [Borovsky et al., 2000].
- The energy input into the thermal electrons from ring current ions and electrons has also been investigated [Liemohn et al., 2000b; Khazanov et al., 2000a]. These studies focused on the heating of the topside ionosphere and the subsequent effects of this energy deposition on the thermosphere and ionosphere. The results were put into

perspective by comparing their values with other known inner magnetospheric heat inputs. It was determined that photoelectrons are the largest dayside supplier of energy while the ring current dominates the nightside energy deposition during geomagnetic storms. The electron component of the ring can provide as much or more heating to the thermal plasma as the ion component. This is especially true on the dawn side during geomagnetic disturbances [Khazanov et al., 1998].

- The team has been actively involved in preparing a number of invited review articles on ring current and related topics. A review article on the high-altitude energy sources for SAR-arcs based on previous research under this same grant was published in Reviews of Geophysics [Kozyra et al., 1997b]. We are currently working on several more invited review articles including: an analysis of the definition and use of the Dst index [Kozyra et al., to be submitted to J. Atmos. Solar-Terr. Phys., 2000], a summary of recent developments in ring current modeling [Kozyra et al., to be submitted to J. Geophys. Res., 2000], a collection of recent research results on the plasmasphere, including hot plasma influences [Ganguli et al., 2000], and an overview of superthermal electron modeling and theory [Khazanov and Liemohn, 2000]. These have served an integral role in our ring current analysis, collecting information on the latest studies and understanding them enough to prepare robust reviews on the subjects.

Major Model Improvements

The University of Michigan version of the Ring Current-Atmosphere Interaction Model (RAM) has undergone several modifications during the last grant period.

- The magnetospheric electric field now has the option of being based on the midnight equatorward edge of the auroral oval, a parameter available on the Internet (for instance, from Air Force DMSP webpages). This allows for the inclusion of rapid time variations in the magnetospheric electric field strength, on a time scale of minutes rather than the 3-h Kp index cadence. Results including this modification are being prepared for publication [Kozyra et al., to be submitted to J. Geophys. Res., 2000].
- Testing continues on the implementation of a non-dipolar and time-dependent magnetic field, and new results are expected shortly. At the present time, a magnetopause algorithm adjusts the outer boundary of the model whenever high solar wind dynamic pressure moves the magnetopause inside the model volume.
- The major new code development is actually in the post-processing software. We have developed several new output products, including (1) a detailed examination of the sources and losses due to each physical process for the purposes of tracking the energy balance during magnetic storms and (2) a Biot-Savart law integration of the simulation results to produce local-time-dependent magnetic field perturbation maps analogous to those produced by chains of ground-based magnetometers [Clauer et al., 1999].
- Changes in the nightside boundary condition were incorporated in the RAM model. An algorithm has been developed to determine if observations by a given satellite at

the outer boundary of the model are on open or closed drift paths. This is an important consideration because variations in the satellite observations are assumed to be due to temporal rather than spatial changes in the nightside plasma sheet and are assumed to extend across the entire open drift path region. Populations on closed drift paths are calculated in the simulation model and are compared to measured fluxes as a test of the model performance.

- A parallelized version of the RAM model has been developed and is in the process of being tested. This will allow simultaneous calculation of all ring current species and is critical for simulation of wave-particle interactions where different ring current populations are responsible for amplifying and damping waves. This couples the evolution of the different ring current ion species. The singly-charged ring current ions evolve independently under all other major loss processes.

Contributions to Research Campaigns

- We have done work on two major magnetic storm studies, in association with: (1) the Brazil VI workshop in Athens, Greece and (2) the SHINE-GEM-CEDAR magnetic storms campaign. These two collaborative efforts require that we simulate the following storm intervals: 4-7 June 1991, 14-17 May 1997, 24-27 September 1998, and 14-22 October 1998. So far, two storms have been simulated: June 4-7, 1991, and September 24-27, 1998 in preparation for the Brazil VI workshop. We plan on investigating the impact of plasma sheet characteristics (density, temperature, composition) on the ring current formation, our ability to predict the ring current from just upstream solar wind plasma and IMF characteristics, the relationship between LT variations in magnetometer signatures and the LT asymmetries in the ring current, the importance of losses out the dayside magnetopause in producing a two-phase decay, the magnitude and timing of precipitation losses, and other issues. Additionally, results of these calculations are being used to examine the influences of hot populations on the development of the low-energy thermal plasma in the inner magnetosphere (that is, on plasmaspheric refilling). We expect this effort to be extremely productive due to the large collaboration effort by the world-wide space physics community in analyzing these events. Two to three journal articles are anticipated as a result of these detailed studies. Preliminary were presented at a number of meetings and conferences (namely Brazil VI in Athens, the Spring 1999 AGU Meeting in Boston, the 1999 GEM Workshop in Colorado, and the 1999 IAGA Meeting in England)

Major Collaborations

- We are also working with the BATS-R-US global MHD model to investigate the entry of solar wind particles into the inner plasma sheet. Statistical work by the LANL MPA team has shown that the density of the inner plasma sheet increases to anomolously high values during times of high solar wind density and the plasma sheet temperature is correlated with high solar wind velocity. These two plasma sheet parameters directly influence the strength of the storm-time ring current. Initial results from the BATS-R-US model are in agreement with statistical results and were presented at the 1999 AGU Fall Meeting. We intend to continue with this project in the next grant period to isolate the mechanism for entry and to run a suite of steady-state simulations, which cover the nominal range of solar wind density and velocity values during magnetic storm conditions.

- We have begun an investigation into the formation and loss of the electron ring current and its impacts on the global suprathermal electron populations in collaboration with Dr. G. V. Khazanov at the University of Alaska. This study is examining the evolution of a plasma sheet source population injected into the plasmasphere, treating energies from a few eV up to 10's of keV [Khazanov et al., 1998]. A second paper on this investigation is currently under review, focusing on the energy deposition into the topside ionosphere.

Special Contributions:

To the Development of the Space Science Discipline

One PI of this proposal, Janet Kozyra is playing a key role in organizing two large community campaign efforts aimed at understanding the flow of energy from the sun to the Earth during magnetic storm intervals. Both are international in scope.

- Janet Kozyra, has been heavily involved with coordinating the SCOSTEP S-RAMP Space Weather Month Campaign. During this interval 5 magnetic storms occurred, 4 associated with corotating interaction regions in the solar wind and the last with a coronal mass ejection. An extensive collection of data from SOHO, POLAR, WIND, ACE, GEOTAIL, OERSTED, ground-based radars, ionosondes, optical instrumentation and riometers is available for these events and will be analyzed jointly by the solar, magnetospheric and ionospheric communities. The NASA ISTP program is a sponsor of this campaign. Dr. Kozyra is developing web access to data sets, working with the Space Physics and Aeronomy Research Collaboratory (SPARC) to design electronic workshop interfaces and organizing meetings specific to discussing science results and developing collaborations. This is of benefit to the entire science community as a testbed for enhancing the interaction and communication between normally separate research communities during large scale, interdisciplinary campaigns. These campaigns which integrate the science of the global Sun-Earth system are becoming a standard mode of operation for the conduct of science in space physics and aeronomy and will continue to be an important mode for science progress in the future. One of the primary web sites for campaign coordination has been developed by the PI of this proposal at URL <http://aoss.engin.umich.edu/intl_space_weather/sramp>.
- Janet Kozyra has also been working with the NSF GEM program over the past 3 years as one of the co-Chairs of the Inner Magnetosphere Storms Campaign. NASA has a collaborative role in this campaign through its ISTP program and through individual NASA-funded researchers who are leveraging the resources

and interactions available in the GEM program to enhance NASA SR&T programs. The primary science focus is to examine magnetic storms and the flow of energy through the Sun-Earth system during magnetically active periods and to develop modeling tools to represent this global system. Dr. Kozyra is also the magnetospheric liaison for the CEDAR-GEM-SHINE magnetic storms campaign which joins together the magnetic storm campaigns of the ionospheric, magnetospheric and solar communities.

- In carrying out the role described above, the PI is performing the following professional service functions:
  - ⇒ Member, NSF's GEM (Geospace Environmental Modeling) Steering Committee 1997-2000.
  - ⇒ Co-Organizer, SHINE-GEM-CEDAR Magnetic Storms Campaign Workshops, June 1999 and May 2000
  - ⇒ Co-Chairperson, GEM Inner Magnetosphere/Storms Campaign
  - ⇒ Member, SCOSTEP S-RAMP Committee on International Space Weather Efforts
  - ⇒ Member, WWW Committee for the Space Physics and Aeronomy Section at the American Geophysical Union, 1998.
  - ⇒ Workshop Organizer, The First S-RAMP Conference, Sapporo/Japan, October 2-6, 2000

To education and development of human resources?

- Supported two graduate students, Vania Jordanova and Joe Manciewicz. An REU student, Heather Orow (1998). Summer of 1999 worked with the Minority Engineering Office at U of M to provide research experience for a female minority high school student from Puerto Rico.

To physical, institutional, and information resources for science and technology?
To the public welfare beyond science and engineering?

To Public Outreach & Education

- Janet Kozyra continues to maintain a science outreach web site that deals with educational and near real-time space weather information which was developed in collaboration with Windows to the Universe (PI: Roberta Johnson), Rice Connections (PI: Patricia Reiff) and WeatherNet 4 (PI: David Jones) public outreach activities. The site's URL is <http://windows.engin.umich.edu/spaceweather>.
- As a member of the AGU web site committee, Janet Kozyra is developing a new portion of the web site which provides access to real-time space weather information using enhanced capabilities for displaying and archiving this information provided by the Space Physics Research Collaboratory (SPARC). The real-time access will provide a showcase for community efforts, an archive

of quick-look real-time data for space weather events for community members and information to science writers in support of AGU press releases. The real-time interface will appear on the AGU web site at URL < http://espsun.space.swri.edu/SPA/>.

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