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Introduction to special section on "Results of the National Science Foundation Geospace Environment Modeling Inner Magnetosphere/Storms Assessment Challenge"

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[1] The National Science Foundation sponsors the Geospace Environment Modeling (GEM) program, devoted to understanding the scientific underpinnings for the creation of a Geospace General Circulation Model. The GEM program is organized into finite-length campaigns, one of which is the Inner Magnetosphere/Storms (IM/S) Campaign, which is ending in 2006. The final activity of the IM/S Campaign was the IM/S Assessment Challenge (IMSAC), in which several events were selected for intense, community-wide examination. The primary purposes of the IMSAC were (1) to quantify the ability of the current set of inner magnetospheric models to predict the fields and plasma of this region during storms and (2) to codify the consensus understanding of inner magnetospheric physics. This paper introduces the reader to the IMSAC and presents a general answer to each of the IMSAC goals. In addition, highlights of the scientific advancements during the IM/S Campaign are presented for the plasmasphere, ring current, and radiation belts, along with a synthesis view of the inner magnetosphere. The biggest need for inner magnetospheric research in the near future is the continued progression toward a coupled, interconnected understanding of this region, especially the nonlinear feedback mechanisms between the plasma populations, the electric and magnetic fields, and plasma waves.

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1. Inner Magnetosphere

1.1. Space Weather Frontier

[2] The inner magnetosphere is an important region of outer space because it is one of the primary locations for space weather effects. Big magnetic storms in space cause severe distortions of the electric and magnetic fields of near-Earth space, and the various inner magnetospheric plasma populations undergo dramatic dropouts, enhancements, and complicated dynamics. This is a region where the Sun's electric and magnetic environment has a very real influence on life and society here on Earth.

[3] In addition to electric and magnetic fields, there are three main plasma populations in the inner magnetosphere: the plasmasphere, ring current, and radiation belts. Each of these populations has distinct features that make it a vital component of the inner magnetosphere. Table 1 summarizes some of their major characteristics. They have very different densities and temperatures, as well as source populations and dominant driver terms in their transport and dynamics. In addition, they each have a separate reason for being important. The plasmasphere dominates the mass density and is therefore a catalyst for plasma wave excitation and interaction with the charged particles in the region. The ring current dominates the energy density and therefore dominates the plasma influence on the near-Earth electric and magnetic fields. Its dominance of the region 2 field-aligned currents means that it also controls the magnetosphere-ionosphere coupling at middle and low latitudes, causing complex ionospheric drifts and density irregularities. Yet another influence is that the electron ring current is responsible for spacecraft surface charging, which is a large source of adverse space weather effects on satellites. The radiation belts dominate the damaging effects to near-Earth spacecraft, including deep dielectric charging within satellites, single-event upsets in electronics, and harm to biological cells (in particular, those in astronauts).

[4] Therefore the inner magnetosphere is at the frontier of space weather, and a firm scientific understanding of this region is important for predicting the interaction between space environmental conditions and human activities. This is especially true as our society becomes more dependent on space-faring technologies, and also as we pursue a renewed interest in human space flight beyond the gravitational confines of our planet.

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Table 1. Characteristics of Inner Magnetospheric Plasma Populations

Population	Density	Temperature	Source	Composition	Driver	Importance
Plasmasphere	100s cm^{-3} to 1000s	<1 eV, maybe up to 10s of eV	Subauroral ionosphere	H^+, some He^+ and O^+	E field	Dominates mass density
Ring current	~few cm^{-3}, up to 10s	1–400 keV	Plasma sheet (SW and iono)	H^+, O^+ in storms	E and B fields	Dominates energy density
Radiation belts	$\ll 1\ cm^{-3}$	100s of keV to MeV	Plasma sheet, SEPs, local acc.	Mostly e-, some H^+	B field	Dominates S/C damage

1.2. Inner Magnetospheric Community

[5] To facilitate and accelerate our understanding of outer space, the National Science Foundation's (NSF) Division of Atmospheric Sciences created several programs specifically designed to focus the space science community's efforts on certain topics. One of these is the Geospace Environment Modeling (GEM) program, which was created as the magnetospheric community's contribution to the global change program of the mid-1980s. The centerpiece of the GEM program is the annual workshop, usually held in Snowmass, Colorado in late June.

[6] The GEM program is conducted as a series of campaigns, each focused on a region or process within geospace, and each lasting a finite length. One of these campaigns is the Inner Magnetosphere/Storms (IM/S) Campaign. Planning meetings were held at the 1996 and 1997 summer workshops, and the first scientific break-out sessions for the IM/S Campaign were held at the 1998 workshop. Even in 1998 it was not quite a full campaign yet, as it still consisted of several planning sessions, specifically to develop the research strategy for the duration of the campaign. By 1999, it was in full swing, and continued to grow in size (both in attendees and break-out sessions) for several years. It reached its climax at the 2005 summer workshop with 14 break-out sessions (some held jointly with other campaigns). The 2006 workshop marks the end of the IM/S Campaign, however, with a scaled-back set of sessions (only eight), mostly focused on wrapping up the various activities of the campaign and seeking ways to pass on the unresolved scientific issues to other campaigns of the GEM program.

[7] The IM/S Campaign is divided into three working groups: (1) plasmasphere and ring current, (2) radiation belts, and (3) ULF waves. Each working group is striving to enhance our understanding of its topical focus through coordinated, community-wide investigations of particular events and phenomena. A few magnetic storms, known as the GEM Storms, were selected early in the campaign life for group-wide study. This list has been extended over the years to include almost a dozen events, and the "GEM Storms" sessions were becoming a potpourri of individual science results, rather than a concentrated effort on a few storm intervals. A climatic activity was therefore introduced to refocus the IM/S Campaign's attention on a short but well-selected list of events: the Inner Magnetosphere/Storms Assessment Challenge (IMSAC).

1.3. Inner Magnetosphere/Storms Assessment Challenge

[8] The IMSAC is a final activity of the IM/S Campaign where the data analysts and modelers worked together to compile our knowledge of the inner magnetosphere. There are two main goals of the IMSAC. The first goal is this: to what accuracy can the existing inner magnetospheric models predict the state of the fields and plasma? A related question to this is what level of model sophistication is needed to get a certain level of accuracy in the results? The second goal is this: what is the present consensus understanding of inner magnetospheric dynamics? A related question to this is what is the full set of physics for a complete description of the inner magnetosphere? An additional outcome from the IMSAC is the definition of metrics for inner magnetospheric model results. This will allow future modelers to benchmark their simulation tools against a known quantity. The accuracy-versus-sophistication improvements over time can then be charted relative to other available codes.

[9] The IM/S working groups addressed the definition of the challenge in different ways. Working Group 1 (plasmasphere and ring current) quickly identified storms and data sets and compiled an ftp site for data dissemination. Working Group 2 (radiation belts) proceeded more cautiously, first identifying science questions that still needed to be answered and then selecting events appropriate for addressing these issues. Working Group 3 (ULF waves), which started halfway through the IM/S Campaign's lifetime, decided not to select their own intervals, but rather to support the other two working groups with their challenge efforts.

[10] Working Group 1 selected two events for their part of the IMSAC. These were the storms of 22 April 2001 and 21–23 October 2001. Both events occurred the same year during solar maximum about a month after equinox. The April storm was driven by a very nice magnetic cloud, with a southward axial magnetic field. The Dst minimum was only −102 nT and so fit the request for a fairly moderate storm in the IMSAC event list. The main phase lasted more than half a day (as the cloud passed Earth), allowing for excellent data coverage of the build up of the ring current and erosion of the plasmasphere. For instance, the IMAGE satellite reached apogee right in the middle of the main phase and was coming back for another apogee pass by the time of Dst minimum. There was good multisatellite measurement coverage at geosynchronous orbit across both the dayside and nightside throughout the event by the spacecraft operated by Los Alamos National Laboratory (LANL).

[11] The October storm had two main phases. The first one was driven by the sheath of a magnetic cloud, and the second storm was from the cloud itself. The first Dst minimum was −187 nT, with a very quick main phase. On 22 October, Dst reached a relative maximum of −129 nT and then drops again (as the interplanetary magnetic field, IMF, turned southward during the second half of the cloud) to the second minimum of −165 nT early on 23 October. IMAGE was at apogee throughout the first main phase, and reached apogee right at the time of the second Dst minimum.

Preference was given to analysis of the first main phase, but both are interesting and included in the IMSAC.

[12] Specific data sets were discussed and selected for the IMSAC events, and researchers were encouraged to compare their model results with these data and use these data in their studies. However, in the end, it was left to the discretion of each individual as to which measurements to include in each study. The most complete set of measurements selected by Working Group 1 is archived as supplemental files accompanying *Liemohn et al.* [2006].

[13] Working Group 2 also selected just two events for intense examination. These were the radiation belt enhancement event associated with the 21–23 October 2001 storm sequence and a similar one during 4–9 September 2002. The September 2002 event was also a double storm event (Dst minima of −109 nT on the 4th and −181 nT on the 8th), driven by a series of solar ejecta, and causing the outer zone radiation belt to be highly dynamic, waxing and waning several times during this interval. For each event, relativistic electron data (from many spacecraft: LANL, GPS, NOAA/GOES, and Polar) was collected and converted into phase space density using a variety of magnetic field models. These results were then made available to the community for analysis and comparison against radiation belt models. For the radiation belts, the main scientific question to be addressed by this challenge concerns the balance of acceleration, transport, and loss mechanisms for relativistic electrons during and after storms.

[14] In the sections below, the highlights of the IMSAC and the IM/S Campaign in general are presented. This is not meant to be a comprehensive list of achievements during the last 8 years but rather a representative summary of major advancements. A discussion of where the inner magnetospheric community should go from here is given, along with a brief conclusion section.

2. Recent Major Advances in Inner Magnetospheric Science

2.1. Plasmasphere Advances

[15] Plasmaspheric research has undergone an amazing revitalization since 1998. This is due to the emergence of new data sets (from IMAGE EUV and RPI), new data analysis techniques (deconvolving ground-based magnetometer data for field line mass content, and total electron content from GPS receivers), and new modeling capabilities (especially the coupling of plasmaspheric models with ring current models). Major advancements have been made in global morphology, electric and magnetic field effects, plasmaspheric refilling, and understanding plasmaspheric mass density.

[16] In terms of global plasmaspheric morphology, the IMAGE EUV database has made a significant contribution to the field. This has been summarized in several recent reviews [e.g., *Sandel et al.*, 2003; *Burch*, 2005], and numerous papers using this data set. Of key importance is the visualization of the plasmaspheric drainage plume [e.g., *Burch et al.*, 2001; *Sandel et al.*, 2001], showing its connection to the main plasmasphere throughout the storm sequence, including the way it narrows and eventually wraps itself around the plasmasphere. Interesting features of the plasmapause have been identified, such as shoulders and fingers (outwardly expanded regions of broad or narrow extent, respectively) and notches channels (inwardly depleted regions of broad and narrow extent, respectively) [*Sandel et al.*, 2003]. In combination with modeling, explanations have been given for many of these features, such as overshielding as the cause of dawnside shoulders [*Goldstein et al.*, 2002], electric field propagation fronts as the reason for undulations [*Goldstein et al.*, 2004], and small-scale electric potential extrema as the source of deep notches [*Gallagher et al.*, 2005].

[17] Numerical modeling has also greatly contributed to our understanding of the global morphology of the plasmasphere. Subauroral polarization streams (so-called SAPS) have been shown to sharpen the outer edge of the drainage plume and enhance the dayward flow of the plasma [e.g., *Goldstein et al.*, 2003, 2005b]. Various electric field models have been shown to be useful for replicating the plasmapause location during storms [e.g., *Liemohn et al.*, 2004, 2005]. The distortion of the magnetic field has also been shown to be an influencing factor on the plasmapause topology, although a minor one compared with the dominant influence electric field [*Goldstein et al.*, 2005a; S. Sazykin, manuscript in preparation, 2006].

[18] Plasmaspheric refilling has been shown to occur in a two-step process, with an initial slow refilling rate followed by a faster refilling rate up to its quiet time, saturated density level [e.g., *Lawrence et al.*, 1999]. It is thought that the first step is dominated by field-aligned flows from the ionosphere into the recently emptied plasmasphere, a time when few collisions occur because the densities are low. The second phase is marked by the existence of an isotropic distribution that allows for more rapid filling because of increased collision frequencies. Furthermore, the IMAGE RPI instrument has greatly contributed to our understanding of the distribution of cold plasma along inner magnetospheric field lines [e.g., *Reinisch et al.*, 2001a, 2001b]. In active sounding mode, radio pulses can be ducted along field lines inside the plasmasphere, and a return signal can be processed to reveal the instantaneous density structure along the field line. The density profiles during quiet times or storms do not follow diffusive equilibrium but rather are "flatter" near the equator, with less latitudinal variation (at low latitudes) than theoretically predicted [*Reinisch et al.*, 2001b, 2004]. Conversely, this means that the latitudinal variation at higher latitudes is steep.

[19] Another intriguing result is the discovery of a relative maximum in density at the magnetic equator [*Denton et al.*, 2006]. Interestingly, however, it is not seen in the inner magnetosphere but rather beyond geosynchronous orbit. This equatorial peak fits the profile of three theoretical predictions. The first is that of a shock wave propagating from the equator towards the ionospheric footpoints of the field line, scattering particles and increasing the density along the way [e.g., *Guiter and Gombosi*, 1990; *Guiter et al.*, 1995]. The second is that of a small field-aligned electric field, created by the coexistence of hot ions (i.e., ring current), slowing the propagation of the refilling streams from the ionosphere [*Liemohn et al.*, 1999, 2000]. It could also be the result of wave-particle interactions transversely heating the cold plasma streams near the magnetic equator, causing localized trapping at this location [e.g., *Singh and Chan*, 1992; *Takahashi et al.*, 2004].

[20] The usage of ground-based magnetometer data sets for plasmaspheric research finally came of age during the GEM IM/S Campaign. A few sessions at the GEM Workshop each year were devoted to this, and it was one of the primary reasons for starting the ULF Waves Working Group. The inner magnetospheric mass density matters because the wave-particle interactions in this region are dependent on the ion composition. An interesting result from this analysis is the quantification of the mass density in the plasmasphere. For example, *Berube et al.* [2005] showed that the quiet time plasmasphere has an average mass close to 1 amu, while the disturbed time plasmasphere has an average ion mass of 4 to 12 amu, rising with increasing radial distance. Another fascinating outcome is the development of magnetoseismology. A good illustration of this type of study is *Chi and Russell* [2005], who showed that the transit time of a solar wind pressure variation through the magnetosphere is related to the mass density of the plasma through which it travels, and they can extract a density profile from the delay time of the signals.

[21] Plasmaspheric research has undergone a revitalization during the IM/S Campaign, and our understanding of these cold, charged particles has vastly improved in recent years. Because of its dependence on the inner magnetospheric electric and magnetic fields, though, it should not be considered as an isolated population but rather should be considered as an integral component of a larger system in near-Earth space.

2.2. Ring Current Advances

[22] Our knowledge of the ring current has also undergone a major transformation during the course of the IM/S Campaign. As with the plasmasphere, this progress is directly related to the availability of new data sets (such as IMAGE HENA and MENA), new data analysis techniques (such as inversions of these images), and new modeling applications (such as coupling between ring current codes and electric and magnetic field models). Major advancements have occurred in the areas of ring current morphology, feedback with the electric and magnetic fields, connection to the plasma sheet, and interactions with plasma waves.

[23] It is now accepted that the storm-time ring current is usually not a ring at all but rather a partial (asymmetric) ring, especially in the main phase and early recovery phase of storms. The main phase ring current has been shown to consist primarily of plasma on open drift paths with the ring current becoming symmetric about the Earth only in the recovery phase [e.g., *Liemohn et al.*, 2001a, 2001b; *Mitchell et al.*, 2001; *Pollock et al.*, 2001]. The IMAGE spacecraft has been particularly fruitful for quantifying storm-time ring current morphology. For example, *Brandt et al.* [2002a] showed strange local time distributions of the ring current for a particular storm (a partial ring current peaked near noon), explaining it as the effect of wave-particle interactions altering the pitch angles and thus the observed energetic neutral atoms reaching the IMAGE spacecraft. Several studies have shown large asymmetries in magnetic field and particle data of the inner magnetosphere [e.g., *Lui*, 2003; *Le et al.*, 2004; *Jorgensen et al.*, 2004].

[24] Another unexpected finding from the IMAGE HENA data is that the nightside pressure peak is not always in the evening sector, as expected from simple theoretical calculations but rather is sometimes in the postmidnight sector [e.g., *Brandt et al.*, 2002b]. This was explained by *Fok et al.* [2003] as a direct result of the midnight potential well, which is generated by the partial ring current [e.g., *Ridley and Liemohn*, 2002]. This potential well distorts the electric fields in the inner magnetosphere, forcing particles toward the dawn sector before convecting them around the duskside of the Earth. At the westward end of this potential well, there is a convergence of equipotential lines, forming the strong radially outward electric fields known as SAPS [e.g., *Fok et al.*, 2003]. The biggest point of this is that ionospheric conductance plays a critical role in ring current development, especially in the midlatitude nightside. Numerous other studies have also examined this connection [e.g., *Sazykin et al.*, 2002; *Garner*, 2003; *Jordanova et al.*, 2003; *Ebihara et al.*, 2004; *Liemohn et al.*, 2005, 2006], showing that the conductance level in the region of partial ring current closure can strongly perturb the inner magnetospheric electric fields from the typical large-scale convection pattern.

[25] The existence of evening-sector flow channels in the inner magnetosphere was also revealed recently [*Chen et al.*, 2003; *Khazanov et al.*, 2004]. These are localized regions of enhanced westward electric field, resulting in fast inward transport of plasma sheet material to quickly form a strong ring current. It is still unknown how these flow channels relate to substorms; a direct connection is not obvious, or how they relate to the magnetosphere-ionosphere coupling issue described above.

[26] Recent results have also demonstrated the influence of the ring current on the inner magnetospheric magnetic field configuration and the importance of this configuration on ring current dynamics. Several recent studies have shown that the magnetic field choice can alter the total energy content of the ring current by up to a factor of two (a more stretched field decreases plasma content) [e.g., *Lemon et al.*, 2004; *Ganushkina et al.*, 2005, 2006; *Zaharia et al.*, 2005, 2006; *Chen et al.*, 2005a, 2006a]. For example, *Ganushkina et al.* [2006] showed that inductive electric field pulses, in addition to a realistic magnetic field, are necessary for reproducing the detailed time series of the Dst index. *De Zeeuw et al.* [2004] showed that even the global magnetic field configuration is altered by the presence of a ring current in the inner magnetosphere, showing that the tail is stretched by the presence of a stronger ring current, and the neutral line is moved back. Global models have also been used for examining the ring current source population [e.g., *Li et al.*, 2005; *Zhang et al.*, 2006b]. A consistent feature of global MHD models without this kinetic model coupling is that the storm time inner magnetospheric field is understretched [e.g., *De Zeeuw et al.*, 2004; *Huang et al.*, 2006]. The implication of these results is that realistic magnetic field models of the inner magnetosphere must include a self-consistent description of the ring current.

[27] In addition to the electric and magnetic fields, the plasma sheet plays an essential role in the creation of the ring current. *Ebihara and Ejiri* [2000] quantified the influence of the plasma sheet temperature on the resulting ring current intensity, finding an ideal temperature of $\sim$5 keV for maximum ring current growth. This is a bit cooler than the average quiet time temperature in the near-Earth plasma

sheet but helps explain why intense storm activity often has reduced temperatures at geosynchronous orbit [e.g., *Denton et al.*, 2005; *Zhang et al.*, 2006a]. The plasma sheet density is also critical in determining the final strength of the ring current. For example, *Kozyra et al.* [2002] and *Liemohn and Ridley* [2002] noted blatant examples of times when the plasma sheet density dramatically reduced before the convection electric field subsided, resulting in fast flow-out loss (convection to the dayside magnetopause) of the storm time ring current (the high-density ring current was rapidly replaced by a low-density one). *Kozyra and Liemohn* [2003] and *Liemohn and Kozyra* [2005] quantified this effect, showing that only flow-out can yield a two-step decay of the ring current. Observationally, *Keika et al.* [2006] conclude that charge exchange only dominates the loss rate of the ring current when the total loss rate is small.

[28] A final ring current topic to be covered here is that of plasma waves, specifically electromagnetic ion cyclotron (EMIC) waves generated by the anisotropic pitch angle distribution of the storm time ring current. These waves are most readily excited in the region of ring current-plasmasphere overlap because of the high thermal plasma density and the local ring current anisotropy. Here, EMIC waves cause pitch angle scattering and strong localized precipitation into the upper atmosphere of both ring current ions [e.g., *Jordanova et al.*, 1998, 2001] and relativistic electrons [e.g., *Albert*, 2003]. Such precipitation has been associated with detached proton arcs seen in the afternoon sector during active times [e.g., *Spasojevic et al.*, 2004]. Recently, *Khazanov et al.* [2003, 2006] has coupled a wave energy density calculation to a ring current simulation, revealing the interplay between the particles and the waves, including intense but localized energy deposition to the plasmasphere via Landau damping. As noted by *Jordanova et al.* [2006], these losses are very strong in certain regions but are a minor component (up to 10%) of the total ring current loss rate.

[29] Results obtained in the GEM IM/S era have definitively shown that the ring current is tightly coupled to the electric and magnetic field topology of the inner magnetosphere. Therefore future progress on understanding the storm time ring current requires a coupled view of this population with many other populations, fields, and regions of geospace.

2.3. Radiation Belt Advances

[30] The radiation belts were one of the first discoveries of the space age [*Van Allen et al.*, 1958], consisting of relativistic ions and electrons trapped in the inner magnetosphere. The physics that dominate these relativistic particles has been examined ever since. The GEM IM/S Campaign has reinvigorated this old field because new observations (and new analysis of old data) have led to a revisiting of all areas regarding the relativistic electron topic. Researchers have examined our understanding of wave-particle interactions, particularly how plasma waves contribute to acceleration and loss processes. There has been an acceptance of the need to convert relativistic electron fluxes into phase space density [e.g., *Schulz and Lanzerotti*, 1974], allowing for a more thorough analysis of the physical processes, especially regarding the debate about an internal versus external source mechanism for the radiation belts. Global modeling of high-energy electrons has also progressed during the last few years, including data assimilation within these models.

[31] One major development over the course of the IM/S Campaign is the identification and quantification of important plasma waves that influence radiation belt electrons. *Summers et al.* [1998] set the stage for this advancement, pointing out the different waves that can dominate the interaction process as a function of local time and radial distance. ELF and VLF waves inside the plasmasphere pitch-angle scatter and deplete the radiation belts, as do the EMIC waves in the ring current-plasmasphere overlap region (particularly prominent in the plasmaspheric drainage plume). Outside the plasmasphere, VLF chorus can scatter radiation belt electrons in both energy (dominant on the nightside) and pitch angle (dominant on the dayside), causing energization or depletion, respectively. ULF waves resonate with the drift periods of these electrons and radially diffuse them, causing adiabatic acceleration. *Abel and Thorne* [1998] and *Summers and Thorne* [2003] have quantified the scattering lifetimes for a number of these waves, particularly the higher frequency EMIC and VLF waves. *Albert* [1999, 2003, 2004] and *Brizard and Chan* [2004] have made significant progress on improving the quasi-linear diffusion coefficient calculations for these wave modes. The effect of ULF waves has also been demonstrated to be quite important for relativistic electron acceleration [e.g., *Elkington et al.*, 1999; *Selesnick and Blake*, 2000; *Brautigam and Albert*, 2000; *Perry et al.*, 2005].

[32] Studies of relativistic electron phase space density have been successfully used to understand the time variation of outer zone relativistic electrons [e.g., *Selesnick and Blake*, 2000; *Hilmer et al.*, 2000; *Green and Kivelson*, 2001, 2004; *Reeves et al.*, 2003; *Onsager et al.*, 2004; *Chen et al.*, 2005b, 2006b]. Several challenges exist, however, regarding the conversion to phase space density, most notably the description of the inner magnetospheric magnetic field and the intercalibration of data from different satellites [e.g., *Friedel et al.*, 2005].

[33] *Green and Kivelson* [2004] shows a nice case study of analyzing PSD variations to conclude that a particular radiation belt enhancement was due to an ''internal'' source (i.e., acceleration locally within the inner magnetosphere). This is in contrast to others who have found adiabatic diffusion from the near-Earth plasma sheet as the dominant source for the outer zone electrons [e.g., *Bourdarie et al.*, 1996; *Kim and Chan*, 1997; *Barker et al.*, 2005; *Yu et al.*, 2006]. *Varotsou et al.* [2005] showed model results with a clear difference in the radiation belt response from radial diffusion and local acceleration. Observationally, *Chen et al.* [2006b] found some events dominated by each kind of source process. The issue of an internal versus an external source is still one open to debate; the physics is complicated and the true answer is most likely a mix of these two mechanisms.

[34] Understanding the dominant acceleration mechanism is confounded by the simultaneous action of transport and loss processes. With the current set of measurements, it is difficult to fully unravel these terms, and the answer, so far, is ambiguous. Again, plasma waves play a critical role in the loss of relativistic electrons from the inner magnetosphere. Losses due to chorus [e.g., *Lorentzen et al.*, 2001a,

2001b; *O'Brien et al.*, 2003], EMIC waves [e.g., *Summers and Thorne*, 2003; *Albert*, 2003], and plasmaspheric hiss [e.g., *Abel and Thorne*, 1998; *Meredith et al.*, 2002] are significant at certain times and places.

[35] A final advancement to mention here is the advent of global modeling of the radiation belts in recent years. *Bourdarie et al.* [1996] unveiled the Salammbo model that calculates the dynamics of the radiation belts in the presence of radial diffusion and velocity space scattering. More recently, *Varotsou et al.* [2005] have examined energy diffusion in this code leading to substantial acceleration of electrons within the outer zone radiation belt. Several other groups have also developed codes for this purpose. For instance, UCLA [e.g., *Shprits and Thorne*, 2004; *Shprits et al.*, 2006] and Rice University [e.g., *Brizard and Chan*, 2004; *Yu et al.*, 2006] have radial diffusion models that they have used to relate source and loss timescales. Models that take into account the local time asymmetry of the particle distribution have also been developed [*Zheng et al.*, 2003; *Miyoshi et al.*, 2006], which are capable of simulating the local-time-dependence of the source and loss mechanisms. *Khazanov et al.* [1999a, 1999b] have also simulated local-time dependent relativistic electrons in the magnetosphere, for the case of an injected beam rather than a natural source.

[36] There have also been test particle simulations of the global dynamics of the radiation belts. Numerous studies have simulated the trapping of plasma sheet electrons in the fields from a global MHD simulation [e.g., *Elkington et al.*, 2003; *Kress et al.*, 2004; *Perry et al.*, 2005]. All of these are based on the particle tracing code of *Hudson et al.* [1997].

[37] A final advancement to note here is the merging of data analysis and modeling with data assimilation techniques. *Rigler et al.* [2004] used a linear prediction method with a Kalman filter to predict relativistic electron fluxes. *Bourdarie et al.* [2005] presented initial results of ingesting in situ satellite measurements of relativistic electrons into the Salammbo model, and J. Koller et al. (Radiation belt data assimilation and parameter estimation, submitted to *Journal of Geophysical Research*, 2006) have continued this work for a more extended time interval. This technique nudges the model results to fit the observations, revealing where the model falls short in its comparisons with those data and thus indicates where and when the physical processes in the model are inadequate. *Naehr and Toffoletto* [2005] have developed a Kalman filter technique in a physics-based model. It is clear that data assimilation is a powerful tool that is growing in usage throughout geospace modeling, but especially with regard to the radiation belts.

[38] In summary, much is known about the scope of processes that influence radiation belt dynamics during storms. However, many of these mechanisms are still vague and ill-defined. Of the three plasma populations being reviewed here, this one is arguably the least understood.

3. Discussion

3.1. Inner Magnetospheric Coupling

[39] A resonant theme of the results of the IM/S Campaign and the IMSAC is that the inner magnetosphere is a highly coupled system. The community has made substantial progress in separately considering the various components of this region, but much of the recent progress is focused on the connections between these components. The plasmasphere collides with the ring current and radiation belt particles and also serves as a wave-particle interaction catalyst. The ring current governs the electric and magnetic fields in the inner magnetosphere, is the energy source for many of the plasma waves in the region, and also heats the thermal plasma. The radiation belts are excellent diagnostic tracers of the magnetic field topology of the inner magnetosphere, and the relativistic electron dynamics critically depends on the ring current and plasmasphere.

[40] Figure 1 shows a schematic of inner magnetospheric coupling. It shows the interplay between the various plasma populations, electric and magnetic fields, plasma waves, particularly ULF waves, and external influences. Of particular interest in Figure 1 are the external factors affecting the inner magnetosphere. One of these external influences is the ionosphere. It impacts the inner magnetosphere in a variety of ways, such as ionospheric outflow providing a source population to the plasmasphere and ring current, high-latitude electrodynamics processing the solar wind energy input and setting the large-scale electric field pattern, and the midlatitude ionospheric conductance structure, regulating the localized electric fields of the inner magnetosphere. Another important external factor is the plasma sheet, which supplies plasma to the ring current and radiation belts (of both solar wind and ionospheric origin). Of course, all of these external factors are, ultimately, controlled by the solar wind.

[41] The inner magnetosphere is a complicated and dynamic region of geospace, coupled to many other parts of the Sun-Earth system. One of the biggest challenges facing the inner magnetospheric research community is their ability to reach out to other topical communities within the larger heliophysical umbrella, integrating our understanding of near-Earth space processes with the physical understanding of other regions. It is an exciting time to be an inner magnetospheric researcher, expanding beyond our usual scientific horizons to address systems-level issues linking the entire solar-terrestrial domain. Large-scale code-coupling efforts, such as those at the University of Michigan [e.g., *Gombosi et al.*, 2002, 2004; *Tóth et al.*, 2005] and the multi-institutional Center for Integrated Space Weather Modeling [e.g., *Luhmann et al.*, 2004; *Toffoletto et al.*, 2004], are critically important for continued scientific advancement.

3.2. Assessment of the IMSAC Results

[42] Taken together, the papers of the NSF-GEM IMSAC special section specifically address the two primary objectives of the IMSAC. Again, those issues were (1) to quantify the ability of the current set of inner magnetospheric models to predict the fields and plasma of this region during storms, and (2) to codify the consensus understanding of inner magnetospheric physics. Before doing this, let us briefly describe the results from the IMSAC studies.

[43] A number of IMSAC studies focused primarily on the dynamics of the fields and currents in the inner magnetosphere. *Zheng et al.* [2006] deciphered the external drivers that control the intensity and position of the region 2 currents. *Pulkkinen et al.* [2006] analyzed the current systems during the sawtooth oscillation event on 22 October 2001, noting a large partial ring current in the evening sector that

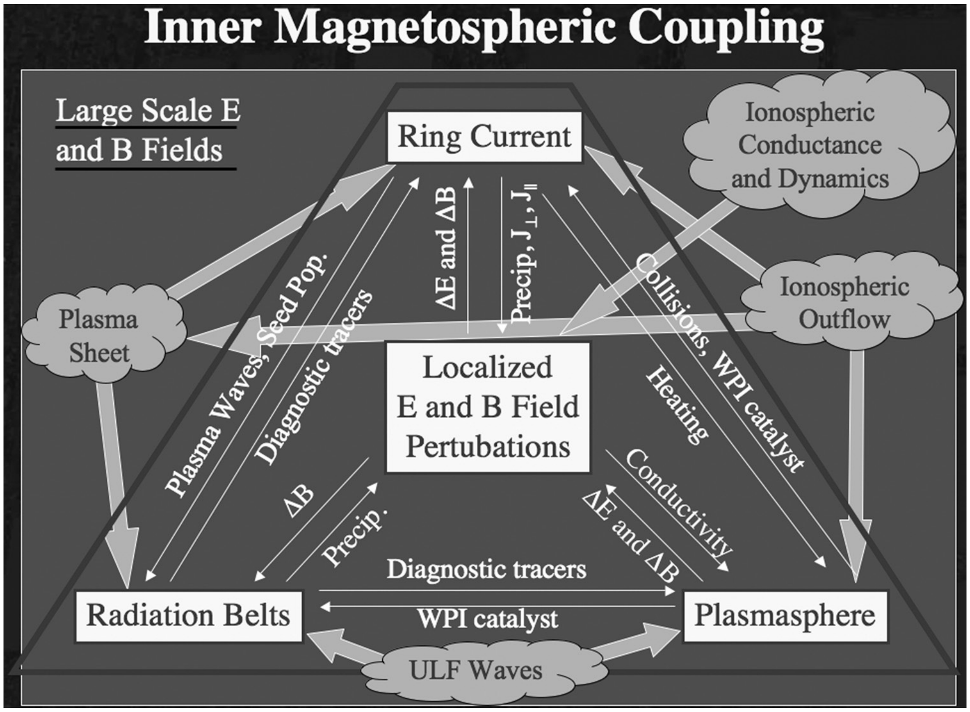

Figure 1. Schematic of inner magnetospheric coupling, showing the linkages between plasma populations and the electric and magnetic fields. The large-scale E and B fields are the foundational underlayment for geospace that influence everything in the figure (the large rectangle behind the other elements), the cloud-like bubbles are external factors that strongly influence the inner magnetosphere, the boxes are the primary populations and fields of the inner magnetosphere, and the arrows show the connection paths between these elements.

causes very fast drifts for the hot ions. *Huang et al.* [2006] assessed the accuracy of an MHD model at predicting the magnetic field at geosynchronous orbit, concluding that, without a kinetic model for the ring current drift physics, the field is not as stretched as the observed distortion during the selected magnetic storms. Several studies examined the influence of a self-consistent magnetic field on the development of the ring current [*Chen et al.*, 2006a; *Zaharia et al.*, 2006], while others examined the influence of a self-consistent electric field on this development [*Jones et al.*, 2006; *Liemohn et al.*, 2006; *Zheng et al.*, 2006]. Most of these studies were quantifying the differences between the inclusion of this feedback effect and its omission, finding large differences that imply the necessity of self-consistency in inner magnetospheric modeling.

[44] A number of studies examined ring current morphology and dynamics during the selected storms. *Milillo et al.* [2006] simulated the April 2001 event with their empirical ring current model, assessing the ring current response to changes in the external drivers. *Jordanova et al.* [2006] and *Liemohn et al.* [2006] used similar models to assess the choice of electric field description on the development of the ring current. It was found that all of the models exhibited some strengths, but, in general, the more sophisticated the electric field description, the better the comparison with observations. *Ganushkina et al.* [2006] presented a comparison between several ring current models, examining the partitioning of the ring current between low (<30 keV), medium (30–80 keV), and high (>80 keV) particle energies. They found that most of the main phase energy is carried by the medium-energy particles, while the late recovery phase was dominated by the high-energy particles. Some took the approach of analyzing the dynamics of a certain part of the ring current, with *Jones et al.* [2006] examining O+ during substorm dipolarizations and *Yamauchi et al.* [2006] addressing the source of the wedge-like low-energy ring current ions on the morningside (they conclude it is substorm injections). A final study on the ring current is that of *Keika et al.* [2006], who analyzed the contribution of charge exchange loss to the decay of the storm-time ring current, finding that it is dominant only when the total ring current loss rate is slow.

[45] A couple of studies examined the plasmasphere. *Goldstein et al.* [2005b] presented several methods for extracting plasmapause locations from the IMAGE EUV measurements, assessing their fidelity and commenting on the fields influencing the plasmapause shape. They also compared it against a model to quantify the electric fields at various times and places. *Liemohn et al.* [2006] assessed the ability of a model to predict various features of the plasmasphere when using a variety of different electric field descriptions, concluding that simple models can, at times, do quite well at reproducing and explaining the observations, but at other times the models were quite poor at matching the data.

[46] Finally, a number of studies examined the enhancements of the radiation belts during the selected events of October 2001 and September 2002. While they used very different approaches (*Chen et al.* [2006b] is purely data analysis, *Miyoshi et al.* [2006] use a kinetic equation model,

and *Ukhorskiy et al.* [2006] employ a test particle simulation), they all reach essentially the same conclusion: an internal source is most likely the dominant mechanism behind the radiation belt enhancements after these storms. There are also some other interesting conclusions as well. For example, *Ukhorskiy et al.* [2006] find that most of the adiabatic ''Dst effect'' reduction of the radiation belts during the storm is actually an irreversible loss of these particles to the dayside magnetopause.

[47] Let us now return to the two IMSAC purposes stated above. In answer to the first question, the present set of inner magnetospheric models is able to accurately reproduce many of the large-scale features of the dynamics of this region. At their best, the plasmaspheric models are able to reproduce the storm-time evolution of the plasmapause to within an Earth radius at all local times throughout the event. At their best, the ring current models are able to reproduce the total energy content of the hot ions to within 20% throughout each storm. The large-scale morphological features of the ring current (e.g., pressure peak location or a particular pressure isocontour) are typically reproduced within an Earth radius. Radiation belt models are often able to reproduce the timing of the relativistic electron dropouts and enhancements. The field has significantly progressed over the course of the IM/S Campaign.

[48] This said, there is still much to do. Plasmasphere models are not able to reliably and automatically reproduce the small-scale features of the plasmapause, and very little has been done to compare the actual density levels within the plasmasphere. Ring current modelers are still exploring the feedback with the electric and magnetic fields, and there is still substantial work to do to fully understand this nonlinear coupling. Radiation belt modelers are still trying to quantify the source of the relativistic electrons (namely, internal versus external source dominance), and they are still trying to fully incorporate the known physical processes that act on these particles. So, while the modeling community has made advancements, and the IM/S Campaign has been pivotal catalyst in promoting this advancement (especially at bringing modelers and data analysts together), many more developments are still needed regarding simulations of the inner magnetosphere.

[49] The second question has been thoroughly discussed in the previous sections. The scientific highlights in section 2 and the coupling schematic in section 3.1 illustrate that one of the most important lessons learned from the IM/S Campaign is the inter-connectedness of the plasma populations in the inner magnetosphere. Truly understanding the coupling between the populations, fields, and spatial regions within geospace is a critical frontier for the research community.

3.3. Areas for Improvement

[50] Let us elaborate briefly on some of the specific areas for improvement in inner magnetospheric research. Regarding the plasmasphere, most of the studies have focused on total electron or ion density and have not fully considered ion mass composition. The plasmasphere carries the bulk of the mass in the inner magnetosphere, and therefore understanding its dynamics, composition, and energetics is highly desirable. Studies of plasmaspheric energetics are nearly nonexistent, and examinations of the temperature structure and evolution and controlling processes are also missing from the literature. The coupling with the ring current and ionosphere needs to be better understood, and the broader issue of understanding the plasmasphere within the dynamics of the global magnetosphere is a relatively untouched issue. Similarly, the relationship of the plasmasphere to the electric and magnetic fields is needed, especially in order to describe issues such as the plasmasphere's small-scale structure, its systematic subcorotation, and refilling after disturbances.

[51] As for the ring current, coupling to other populations, fields, and regions is by far the largest issue facing this field. The ring current is the carrier of the majority of the energy density in the inner magnetosphere, and therefore it dominates the plasma interaction with the currents and fields of this region. The electron ring current is a topic that has received steady but light attention over the years and could definitely use a concerted research effort to advance the field. A final topic to mention here (but certainly not the only one remaining) surrounds the precipitation of the ring current (electrons and ions) into the upper atmosphere and examining the effects of this energy deposition.

[52] The radiation belts probably require the most attention of the three main plasma populations of the inner magnetosphere. Even though the GEM IM/S Campaign has significantly revitalized this field, our quantitative understanding of the radiation belts is still in its infancy. This is largely due to a lack of a reliable magnetic field model for storm intervals. The interpretation of data requires the conversion to phase space density, which depends on an accurate magnetic field model not only locally at the observation location but globally in order to calculate the higher-order adiabatic invariants. This magnetic field is intimately connected to the ring current. Furthermore, relativistic electrons are highly interactive with the ubiquitous plasma waves of the inner magnetosphere. The location, amplitude and other characteristics of these plasma waves are largely controlled by the plasmasphere. Therefore a thorough description of the radiation belts demands a coupled, systems-level view of geospace and a coupled, self-consistent modeling capability that includes the plasmasphere and ring current (as well as the radiation belts). This connection makes relativistic electrons excellent diagnostic tracers of the entire inner magnetospheric region. With the expected development and launch of NASA's Radiation Belt Storm Probes early next decade, right now is the opportune time for scientific advancement in anticipation of that mission.

4. Conclusions

[53] In conclusion, the NSF GEM IM/S Campaign was a success, bringing together the inner magnetospheric research community in a relaxed and informal workshop setting, allowing constructive discussion and debate on the critical issues facing this field. Much progress was made by the active researchers of the IM/S campaign, and even those not regularly attending the summer workshops indirectly benefited from the focus that GEM provided. The climactic event of the IM/S Campaign, the IMSAC, was also a success, resulting in this robust collection of studies that span the breadth of the campaign topics. Our understanding of

magnetic storms, and in particular their manifestations within the inner magnetosphere, is substantially improved because of this endeavor.

[54] There is still much to do, though. In summary, there is a need for better understanding of the coupling processes between plasma populations, fields, and regions. On this topic, self-consistent calculations need to continue to be developed, including global modeling that links the inner magnetosphere to the ionosphere and the outer magnetosphere. In addition, focused attention on plasma waves and other small-scale plasma structures would be greatly beneficial.

[55] The inner magnetosphere is on the frontier of space weather effects on life and society. A renewed focus on this region of geospace is required for avoiding many of the catastrophic negative impacts of space storms on humanity. It is with great hope and expectation that we close out the GEM IM/S Campaign and look forward to the continuation of the collegial atmosphere of discourse within this community that the IM/S Campaign has fostered and promoted.

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