Summary of sessions: Magnetospheric Working Group

A. S. Sharma[1] and J. U. Kozyra[2]

[1] Department of Astronomy, University of Maryland, College Park, Maryland 20742, USA
[2] Atmospheric, Oceanic and Space Sciences Dept., University of Michigan, Ann Arbor, Michigan, 48109-2143, USA

Abstract. The working group on magnetospheric research covered a variety of science issues in solar wind – magnetosphere-ionosphere coupling, with emphasis on geospace storms. The papers were presented in three oral sessions and a poster session, and were summarized for other working groups in two plenary sessions, which also served as forums for discussing cross-disciplinary issues. Among the plenary talks at the workshop at least six were on topics directly related to the magnetosphere. The panel discussion on future collaborations also featured many areas involving studies of the magnetosphere.

Index Terms. Geospace storms, radiation belts, solar wind-magnetosphere coupling, substorms.

1. Introduction

The magnetosphere plays a central role in the coupling of the disturbances on the sun to geospace. In the chain of events connecting solar activity to the Earth, the magnetosphere exhibits a wide range of physical processes that provide this coupling. The magnetosphere, a cavity in the solar wind flow anchored by its dipole magnetic field, exhibits many plasma processes with a wide range of space and time scales. The physical processes in the magnetosphere are essentially of two types: those driven directly by the solar wind and those arising from internal processes. Over the last few decades, a wealth of information on the nature and variability of these processes has been captured by ground-based and space-borne instruments; the combination of viewpoints from these types of data sets is critical for separating spatial and temporal effects. In fact, the rich collection of ground-based magnetometer records and ionospheric observations at various location within India, combined with satellite data sets within the ILWS effort, is one area where collaborations within the ILWS program are likely to result in new discoveries about severe magnetic storm disturbances and mid- to low-latitude aspects of geospace coupling.

For the purposes of this summary, papers in the workshop are divided into the following broad categories:

- Solar wind coupling to the magnetosphere
- Radiation belts and energetic particles
- Waves and fluctuations and their effects
- Storm-substorm relationship and related issues
- Modeling and prediction
- New missions

The highlights of the papers are presented in the following sections. The topics covered in the panel discussion and relevant to the magnetospheric studies are summarized in the conclusion section.

2. Solar wind coupling to the magnetosphere

Solar wind disturbances from different types of source regions on the Sun produce characteristic features in the magnetic activity they drive at Earth. For example, active regions produce coronal mass ejections that can drive intense magnetic storms; while, coronal hole winds produce corotating interaction regions that can drive weaker storms but long (up to 10 day) intervals of recurrent substorms.

These different types of solar wind drivers have occurrence patterns that follow the solar activity cycle: CME's predominate near solar maximum and coronal hole winds in the declining phase toward solar minimum. *Alex et al.*, (PMS1) examined the variation in strong magnetic storm activity, dominantly related to interplanetary CMEs, and thus expected to peak near solar maximum. During solar cycle 23 two intervals of strong activity occurred during the declining phase rather than the main phase – one in late 2003 and the other in early 2005. Both intervals interrupted the relatively smooth decline of activity toward solar minimum; however, the ground-based magnetic field variations in 2003 had a different character than those in 2005; long-lived and intense versus fluctuating, respectively. This work implies that the change in frequency of solar drivers with the solar cycle does not necessarily occur in a smooth manner.

There are also large-scale changes in the heliospheric structure (i.e., a shift from radial flow to higher flow latitudes) associated with disturbances that produce geomagnetic activity [reported by *Pereira and Garish*, M5]. In fact, there is a correlation between Ap and the occurrence of such flows.

Strong shock structures ahead of coronal mass ejections can accelerate solar particles from the corona or from solar flares and enhance ongoing solar particle events. Signatures in magnetometers of shock arrival can be observed at all latitudes. Geospace disturbances from this magnetic activity center first in the high latitude regions on Earth but are quickly transported through ionosphere-atmosphere coupling and electrodynamic effects to a wider range of latitudes, at times reaching as far as the equator. *Vichare and Alex* (PMS6) investigated the relationship between solar wind parameters and one-minute averages of the storm time horizontal component of magnetic field perturbations at Alibag (GMLAT = 9^{o} N). Changes in solar wind density and dynamic pressure were both highly correlated with magnetic field disturbances observed at the Alibag observatory, providing evidence for a direct solar wind impact during magnetic storms even at these low latitudes

(a) Magnetic Activity from Coronal Mass Ejections

Kozyra (M1) presented new information on processes throughout geospace that effect the intensity and duration of electric fields penetrating from high to equatorial latitudes during magnetic storms. The ring current and inner plasma sheet shield the inner magnetosphere and underlying mid- to low-latitude ionosphere from the convection electric field. This shielding is disrupted during times of changing interplanetary magnetic field (IMF) Bz and is reestablished in the inner magnetosphere as ring current particles drift to new locations under the influence of the changing large-scale convection electric field. During this time, high latitude electric fields can penetrate to the equatorial region, dramatically redistributing ionospheric plasma there and triggering instabilities. The ability of the ring current to shield is a function of its density and temperature – low density and/or cool plasma sheets produce ring currents with inefficient shielding [*Garner*, 2003] so penetration electric fields can last for many hours. The density of the plasma sheet (the primary source for ring current particles) is correlated with the upstream solar wind density [*Borovsky et al*., 1998]. Thus the strength and duration of the penetration electric field at low-latitudes is directly related to ring current shielding properties, which vary with IMF Bz and solar wind density.

Sreehari and Nayer, (PMS7) used observations from the ACE, Wind and Cluster satellites (the former two in the solar wind, the latter on field lines mapping to the polar regions) along with magnetometer observations from stations in the IMAGE network (in the polar region) and F-region plasma drifts from the HF Doppler radar at Trivandrum (at 9^{o} N GMLAT) to study the penetration of the convection electric field into the magnetosphere and then from high to low latitudes in the ionosphere during the 20 November 2003 superstorm. Trivandrum and the IMAGE stations along with the Wind satellite on the nightside observed nearly simultaneously electric fields with variations similar to the interplanetary electric field seen by ACE but delayed by 77 minutes.

During magnetic storms, changes in the global electrodynamic coupling between high and low latitudes (such as the penetration of convection electric fields) as well as between the ionosphere and plasmasphere can result in large-scale redistribution of ionospheric plasma. However, measurements of total electron content (TEC) contain both ionospheric and plasmaspheric contributions, making it difficult to understand their relative contributions to variability during magnetic activity. By comparing observations from the Indian CRABEX network of beacon transmitting stations (which observes the ionosphere up to 1000 km) and GPS measurements up to 20,000 km, it is possible to determine the plasmaspheric contribution to TEC (called PEC) [*Ravindran et al*., M13]. PEC provides 10-60% of the TEC varying with season, latitude and time. Observations using this technique during two magnetic storms showed that the equatorial anomaly was suppressed at 1230 LT. More work is needed to understand the underlying physical processes that produced this effect.

Ground magnetometers in India routinely record signatures of interplanetary shocks preceding solar wind disturbances as well as monitoring the ring current build-up and decay from the disturbance itself. The shocks, in addition to producing storm sudden commencements, are associated with the continuing acceleration of solar energetic particles. *Rawat et al*., (M18) compared ground magnetometer observations in India during two magnetic storms (21-22 January 2005 and 5-6 November 2001), which were, associated with strong interplanetary shocks, and solar energetic particle events. However, the January 2005 event (min Dst ~-105 nT) was driven by fluctuating IMF Bz of ± 30 nT near the shock, whereas the November 2001 event (min Dst ~-292 nT) was driven by ~5 hours of strong (down to -77 nT) southward IMF Bz. The enhancement in energetic proton density and the IMF Bz at shock passage showed good correspondence with min Dst in each event. However, no clear trend was seen between ground-based magnetometer signatures and upstream solar wind velocity.

There has been recent interest in the effects of solar wind voids (Nsw < 1 cm-3) on the geospace environment. They produce an unusually expanded magnetopause and allow high energy (up to 10 keV), intense (~ 1 erg cm^{-2} s^{-1}) polar rain to enter the polar caps preferentially in one hemisphere. In quiet times the polar rain can be the dominant energy input creating interesting asymmetries in currents, joule heating and particle precipitation effects between the northern and southern hemisphere [c.f., *Knipp et al*., 2000]. However, little is known about the low-latitude signatures of these events. *Pathan et al.* (M19) reported signatures of an extended solar wind void interval from 15-18 February 2004 associated with a high-speed stream during which the Olson Pfitzer dynamic magnetosphere model predicted a magnetopause distance of 14 RE. Magnetometer observations in India showed that the Sq current system was affected. The diurnal variation of the H component was attenuated. The semi-diurnal variations were more prominent in the D-component. Substorm activity was subdued with no ULF pulsation recorded at the ground.

(b) Magnetic Activity from High Speed Streams

Large coronal holes with extensions to low solar latitudes become more frequent during the decline to solar minimum. The high-speed streams that flow out of the coronal holes create shocks and sheath regions (called corotating interaction regions) as they plow into and compress the slower solar wind ahead of them. The high-speed solar wind from coronal holes contains fluctuating magnetic fields at times with a significant southward component. These fluctuating fields can trigger long intervals (up to ten days) of recurrent auroral activity called HILDCAA (high intensity long duration continuous auroral activity) events [c.f., Tsurutani et al., 1999]. As a result, energy input to geospace can maximize during years of strong high-speed stream activity in the descending phase of the solar cycle even exceeding the integrated input due to major magnetic storms at solar maximum. The most recent peak in high-speed stream activity was in 2003. Auroral energy input in 2003 was larger than at any time during the last 4 solar cycles and produced long-duration intervals of disturbed ionospheric conditions, and increased nitric oxide production important for upper atmospheric cooling and, through downward transport, for stratospheric ozone loss [*Kozyra*, M1]

Sector structure (changes in sign in the IMF Bx, By as a result of the configuration of the heliospheric current sheet) during solar cycle 23 had a global effect on magnetic activity. These sector structures were seen in magnetic observations (all components) at high, middle and low latitudes. [*Zaitzev and Odintsov*, M6]

Variations in EUV associated with coronal hole transits systematically preconditioned the neutral atmosphere and ionosphere - increasing background O/N2 and decreasing total electron content (TEC) prior to the onset of high-speed stream-related magnetic activity. Models predict this should produce deeper penetration in altitude and latitude of magnetic activity effects [*Kozyra*, M1]

The coronal hole solar wind is highly variable and the fluctuations in IMF often have nearly regular characteristics, identified with Alfven waves. *Tsurutani et al*., (M2) presented evidence that auroral activity (HILDCAA events) produced by fluctuating IMF Bz associated with these Alfven waves exhibits differences from auroral substorm activity being less intense and more global in nature. Shallow injections of plasma sheet plasma into the inner magnetosphere may also create conditions unstable to wave growth thought to be important to relativistic electron acceleration.

(c) Primary Driver of Magnetic Activity: Reconnection

Dayside reconnection is the dominant process for transporting solar wind energy and plasma into the magnetosphere. In the ionosphere, this reconnection drives global convection cells that are responsible for many of the signatures of magnetic activity in the ionosphere-thermosphere system. Trattner et al., (M10) presented new ways of investigating features of reconnection using cusp data. Exciting results have been obtained by mapping the location of the 4 Cluster satellites onto convection patterns derived from SuperDARN observations; this technique allows the separation of spatial and temporal features in the reconnection. In one case changes in energetic particles from the reconnection site occurred as Cluster spacecraft moved into a spatially separated convection cell. In another case, a temporal change was observed as a change in the convection pattern moved over the Cluster spacecrafts.

3. Radiation Belts and Energetic Particles

The study of energetic particles in the magnetosphere is an important component of the international space weather program. These particles with energies up to many MeV's can cause significant damage to space-borne technological systems and humans in space. These relativistic particles will be studied in detail by the Radiation Belt Storm Probes under NASA/LWS program.

A study of the energization of electrons in the outer radiation belt using the SAMPEX and Polar measurements was presented by *Kanekal* (M8). The daily average fluxes of electrons in the energy range 2 - 6 Mev since 1998 were used to analyze the storm time enhancement of stably trapped electrons. Many characteristic quantities of the outer zone radiation belt electrons, such as high and low altitude flux ratio, storm time enhancements of stably trapped electrons, global coherence, solar cycle dependence, etc. were obtained. The electron fluxes did not show a clear correlation with Dst in the range between –75 nT and -173 nT. The flux of high-speed streams is found to have a plateau at L = 3 and isotropization is found to lead to increased flux.

4. Waves and Fluctuations and Their Effects

The waves in the magnetosphere show a wide frequency range and they play important roles in different processes. New details were presented regarding ULF waves, nonlinear wave modes, low frequency quasi-electrostatic waves in the ring current region, and waves associated with reconnection.

(a) ULF Waves

Ultra low frequency (ULF) components are ubiquitous and are associated with the oscillations of the magnetospheric field, mainly the dipole component.

Two papers [*Rajaram*, M9; *Sinha and Rajaram*, M11] presented the modeling of these waves and comparison with spacecraft data from AMPTE/CCE, Cluster and Polar spacecraft. The multivariate analysis considers 8 natural orthogonal components to develop an analytic theory of ULF waves (toroidal, poloidal and radial structures). The toroidal and poloidal modes are decoupled and the eigenmode equations, derived using the well-known Mead field model, are solved numerically by using a numerical shooting method. The complete set of nonlocal eigenfunctions can be used to obtain many features, such as equatorial response, local time dependence, interaction with particles, pitch angle distribution, lower latitude particle flux, etc. The effect of changes in the ionospheric conductivity is incorporated through boundary conditions and this yields standing Alfven waves. The changes in the solar wind dynamical pressure lead to excitation of these modes. The data from different spacecraft, such as the Cluster dynamical spectra, are compared with the results of the model.

Important information needed to test possible generation mechanisms for ULF waves comes from statistical studies relating their occurrence in space and time to solar wind parameters. For ULF waves in the Pc3 range, many statistical studies have been carried out at mid- and high-latitudes but far fewer at low latitudes. *Ansari* (PMS10) found a correspondence between the occurrence of Pc3 waves at low latitudes in southeast Australia and solar wind velocities between 400 and 700 km/s in agreement with previous studies. The appearance of Pc3 waves at such small radial distances (L = 1.8 to 2.7) places additional constraints on generation mechanisms. Evanescent surface waves on the magnetopause (one possible source of Pc3 waves) may find it difficult to penetrate to these low L values. Waves generated at the bow shock, swept into the magnetosheath and subsequently coupling into field line resonances are better candidates. The Mach number dependence of the bow shock characteristics provides a natural link between Pc3 occurrence and solar wind velocity.

(b) Nonlinear Waves

Energy extracted from the solar wind is transported between regions in geospace within thin boundary layers. Steep plasma density gradients and currents in these boundary layers contain free energy that can drive plasma waves including nonlinear modes under the right conditions. Such nonlinear waves and associated micro-scale processes can affect the global-scale behavior of the system.

Large amplitude nonlinear waves with 2D structure have been recently observed in the magnetosheath. *Ghosh et al.*, (PMS2) investigate the generation of these waves using electron acoustic and lower hybrid dromion solutions to the nonlinear equations. Dromions are a class of multidimensional (exponentially localized) solitons. The estimated size and shape of electron acoustic dromions are consistent with satellite observations on auroral field lines.

The decay of large amplitude broadband waves, commonly observed on auroral field lines, into kinetic Alfvén waves (KAWs) is investigated by *S. V. Singh et al.*, (PMS5) using a nonlinear dispersion relation describing the 3-wave interaction process. This is one plausible explanation for the appearance of KAWs on auroral field lines important for the acceleration of auroral plasma.

Modeling the energization of auroral particles requires a description of the nonlinear evolution of KAW in three-dimensions. *R. P. Sharma* (M16) described the use of analytical and numerical techniques in the ongoing development of a model of one important nonlinear mechanism, filamentation of KAWs.

Inertial and kinetic Alfven waves on auroral field lines (unlike Alfven waves) are dispersive. *N. Singh* (PMS8) presented an investigation of the implications for Poynting flux calculations. The Poynting flux from dispersive Alfven waves maps with altitude (r) as $B(r)^{1/2}$, while that from Alfven waves maps as B(r). This revised scaling is consistent with observations made by FAST and Polar, as well as Polar and Geotail during conjunctions.

Kinetic Alfven waves are also implicated in the decay of long-scale vortex flow, such as Rayleigh-Taylor instability [*Chakrabarti and Lakhina*, PMS9]. After reaching a threshold amplitude, the vortex begins to decrease in energy due to the release of shorter scale secondary waves (such as, kinetic Alfven waves). These secondary waves are damped in the plasma. Such secondary processes may provide an explanation for the nonlinear saturation of these low frequency vortex instabilities.

(c) Waves in the Ring Current Region

In the inner magnetosphere, ring current distributions contain free energy for the generation of plasma waves but the exact nature of the waves generated and their role in modifying the ring current distributions, as well as in producing precipitation losses, is not yet clear. *Kakad et al.*, (PMS3) reported on the ongoing development of a model of the growth and saturation of low frequency, quasi-electrostatic waves in a 4-component plasma consisting of isotropic cold electrons, cold protons, and energetic protons and oxygen ions with loss cone distributions. These waves are capable of scattering ions into the loss-cone and thus are a candidate process for producing ring current loss.

(d) Simulations of Reconnection

The dynamic changes in the magnetic field in the magnetotail are associated with many plasma processes and the large scale or global changes arise from reconnection at the current sheet. The onset of reconnection has been one of the key problems in the physics of the magnetosphere and one possible mechanism is through surface waves excited at the magnetotail lobes. *Uberoi* (M4) presented a surface-wave induced magnetic reconnection model in the context of the thermal catastrophe model for substorms. In this model Alfvén wave resonance due to the inhomogeneity in the plasma profiles excites the waves that would lead to the thermal catastrophe. However the latter needs significant intensity of Alfvén waves before substorm onset and observational evidence of Alfvén waves is unclear. Also considering the very thin current sheets in the magnetotail during substorm growth phase, further analysis that considers the kinetic nature of the processes is needed to build realistic models.

Recent observations by the Cluster spacecraft of extremely thin current sheets approximately 30 km wide (5-6 electron skin depths on the dayside) have been reported by *Wygant et al*., [2005]. New particle-in-cell simulations of the evolution of thin current sheets and the onset of reconnection, presented by *N. Singh et al*., (M15), reproduce many of the features observed by Cluster.

5. Storm-Substorm Relationship and Related Issues

The storm-substorm relationship, among the oldest and most controversial issues in space physics, has been the focus of many studies (*McPherron et al*., 1997). The detailed analysis of the recent spacecraft and ground based data, as well as theory and modeling, had led to the Lonavala consensus (*Sharma et al*., 2003) that the storm main phase is due to increased convection in the magnetosphere. While the substorms play an important role during storms, it is now recognized that storms are not caused by a succession of substorms alone.

However, a review of the literature by *Lakhina* (M14, Plenary) indicates that the exact relationship between storms and substorms is still unclear. Another aspect of storms, the role of plasma waves in the energization of the ring current particles, also remains an unsolved problem. A set of 9 intense storms with Dst less than -175 nT was used to analyze the energy budget during geospace storms and 5% of the solar wind energy was found to be dissipated in the ring current during storms [*Lakhina*, M14, Plenary]. The IMF Bz duration in these storms determined the duration of the storm main phase, but there was no clear dependence of the minimum Dst on the main phase duration. Other results from the study, include the following: the Halloween storms (October 29 - 31 and 20-21 November 2003) showed no correlation with the changes in solar wind velocity, and the ground magnetometer data from the Alibag observatory showed a delay of 25 minutes from the ACE measurements,

Nayar et al., (PMS4) performed a wavelet analysis of solar wind plasma and IMF parameters compared to variations in the H-component of the disturbance magnetic field to examine the relationship of periodicities in these elements to substorms occurring during magnetic storms. Throughout the storm, stable higher frequency components in the solar wind parameters are found, some with periods comparable to substorm cycle time. These high frequency components may have a role in triggering periodic substorms

A type of auroral activity associated with magnetic storms is the global sawtooth oscillations, evident in the energy spectra of particles measured in the geosynchronous region. The global sawtooth oscillations are essentially substorms in which an unusually large part of the magnetosphere is activated. The role of these sawteeth events in the storm development is an important issue and was discussed by *Clauer* (I1).

6. Modeling and Prediction

One of the key objectives of the International Living With a Star is the development of the state of geospace. Due to the large number of plasma processes in the sun-earth connection and the wide range of space and time scales of these processes, the development of a comprehensive first principles model is still a challenge. The extensive data of the magnetosphere can be used to develop models based on the theory of nonlinear dynamics and complexity and such data-derived models have the advantage of capturing the features inherent in the data, independent of assumptions, and has been used to develop forecasting tools. The global MHD model of the magnetosphere captures the essential features and is now the backbone for the development of more comprehensive models.

A comparison of the data-derived models with the global MHD simulations (Lyon, 2000) is presented in a paper by A. *S. Sharma* (M12). In both these models the magnetosphere exhibits global and multiscale features. The global magnetospheric dynamics is modeled in both cases using time series data and yield the dynamical manifold or surface on which the dynamics evolves. Sudden changes, such as the substorms, are seen as transitions between two levels and such features can be predicted. The multiscale features on the other hand are high dimensional and can be predicted only in a statistical sense. Both the data-derived and MHD models yield power law behavior for the multiscale features but with slightly different indices.

The observational data of the magnetosphere has been used extensively to develop empirical models of the relationships between different physical variables. A prediction scheme for Dst and radiation belt electron fluxes, based on statistics containing largely small to moderate events, produces reasonable predictions even of extreme events. This scheme was presented by *Li and Temerin*, (M3). The model is tested on the 1859 Carrington event (observed by India’s Colaba Observatory) and the October-November 2003 superstorms. For the Carrington event the model predicts 1000 cm^{-3} solar wind density and the shape of IMF Bz needed to match the fast recovery observed by ground magnetometer stations. For the October – November 2003 storms, the model is found to perform better with corrected solar wind data.

7. New Missions

Many new spacecraft missions are planned for monitoring geospace and a striking feature of these is the multi-point measurements. For example, the two Radiation Belt Storm Probes under NASA/LWS program will make measurements in the radiation belts at two locations suitable for studying the spatial correlations. The four spacecraft Magnetospheric Multiscale Mission will explore the magnetotail to unravel the microphysics of magnetic reconnection. The THEMIS mission will probe the magnetosphere with five spacecraft to study the connection between the different region and the underlying processes.

The Solar Polar Orbit Radio Telescope (SPORT) is a new mission concept under study and funded by the Chinese National Science Foundation and the highlights of the mission was presented by *Ji et al.*, (M7). This mission will image high density solar wind structures propagating toward Earth through radio emissions at low frequency (as low as 20-30 MHz). Using synthetic aperture techniques this will enable reconstruction of disturbances from the vantage point out of the sun's ecliptic plane, similar to Ulysses. Such a mission will have the capability to image CME's propagating away from the sun in all directions. Also it can provide support for Mars exploration.

The panel discussion session on future collaborations provided excellent opportunity for exchange of ideas on the science and mission concepts. The discussions ranged across areas covering collaborative space, ground-based and theoretical studies. The growing interest and commitment to space exploration in India was noted with interest by the participants. Considering the growing Indian space science community Sharma suggested a multi-spacecraft mission in conjunction with the NASA MMS mission. Such a collaborative mission would lead to significant enhancements in the science yield of the missions and will provide unprecedented opportunity for the international community to advance space science through joint missions.

8. Conclusions

The working group on the magnetosphere covered a wide range of topics in the study of Sun-Earth connections. The activities, comprised of oral and poster papers, discussions on cross-disciplinary issues, and many exchanges throughout the workshop, led to many new collaborations. The contributions of the Indian space science community to ground-based measurements of geospace were much appreciated in the workshop. In particular the ground magnetometer stations at Colaba and Alibag, with continuous monitoring for more than 160 years, have stimulated new studies such as the analysis of the historic Carrington superstorm of 1859. The distributed ionosondes in India also provide important data for inospheric studies and the development of models. In view of these it was recommended that India should play a major role in the ILWS program, especially in the ground based observations program.

Acknowledgments. The research at the University of Maryland was supported by NASA grant NNG 04GE37G and NSF grant ATM-0318629. The research at University of Michigan for this study was supported by NASA grants NAG5-10297, NAG-10850, and NAG-12772 and NSF grants ATM-0090165 and ATM-0302529.

References

J. E. Borovsky., M. F. Thomsen and R. C. Elphic, "The driving of the plasma sheet by the solar wind", *J. Geophys. Res.,* vol. 103, pp.17617-17640, 1998.

T. W. Garner, "Numerical experiments on the inner magnetospheric electric field", *J. Geophys. Res*., vol. 108, p. 1373, doi:10.1029/2003 JA010039, 2003.

D. J. Knipp, C. -H. Lin, B. A. Emery, J. M. Ruohoniemi, F. J. Rich and D. S. Evans, "Hemispheric asymmetries in ionospheric electrodynamics during the solar wind void of 11 May 1999", *Geophys. Res. Lett*., vol. 27, pp. 4013-4016, 2000.

R. M. McPherron, "The role of substorms in the generation of magnetic storms", in *Magnetic Storms*, *Geophys. Monogr. Ser*., vol. 98, B. T. Tsurutani et al., Eds. AGU, Washington, D. C., 1997, pp. 131-149.

A. S. Sharma, D. N. Baker, M. Grande, Y. Kamide, G. S. Lakhina, R. M. McPherron, G. D. Reeves, G. Rostoker, R. Vondrak and L. Zelenyi, "The storm-substorm relationship: Current understanding and outlook", in *Disturbances in Geospace: The Storm-Substorm Relationship*, Geophys. Monogr. Ser., vol. 142, A. S. Sharma, Y. Kamide and G. S. Lakhina Eds. AGU, 2003, pp. 1-14.

B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, C. M. Ho, G. S. Lakhina, J. K. Arballo, R. M. Thorne, J. S. Pickett and R. A. Howard, "The interplanetary causes of magnetic storms, HILDCAAs and Viscous Interactions", Phys. Chem. Earth (C), vol. 24, pp. 93-99, 1999.

J. R. Wygant, C. A. Cattell, R. Lysak, Y. Song, J. Dombeck, J. McFadden, F. S. Mozer, C. W. Carlson, G. Parks, E. A. Lucek, A. Balogh, M. Andre, H. Reme, M. Hesse and C. Mouikis, "Cluster observations of an intense normal component of the electric field at a thin reconnecting current sheet in the tail and its role in the shock-like acceleration of the ion fluid into the separatrix region", *J. Geophys. Res*., vol. 110, A09206, doi:10/1029/2004JA010708, 2005.