"Effects of Ionospheric-Magnetospheric Plasma Redistribution on Storms"

LWS TR&T Integrated Research Plan

Focus Topic Research Team – Principal Investigators

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1. Project Goals

The overarching goals of the LWS TR&T Focused Research Project on the "Effects of Ionospheric-Magnetospheric Plasma Redistribution on Storms" are to establish

- how the magnetospheric uptake of ionospheric plasma during storms changes as a result of ionospheric plasma redistribution, and
- how this uptake influences the dynamics and coupling of the magnetosphere and ionosphere, with emphasis on the plasma and geomagnetic field conditions of the inner magnetosphere and the evolution of the ionospheric conductance, temperature and densities.

In answering these questions, we will use and advance physical models, empirical models and data sets to analyze and to predict the effects of ionospheric outflows on the global geospace environment and to treat magnetospheric and ionospheric-thermospheric regions as a single connected system, including both electrodynamic and inertial couplings between the regions. The anticipated results will provide a useful touchstone for interpreting measurements, especially mass composition measurements, from satellite missions such as FAST, Polar and Cluster, and they anticipate future needs to interpret distributed measurements of ionospheric and magnetospheric dynamics from the THEMIS and TWINS missions, the LWS Radiation Belt and IT Storm Probes, and the GEC and MMS satellites.

Measures of success include the identification of principal mechanistic features and quantitative assessment of the impacts of plasma redistribution and outflow over the range of stormtime conditions and solar wind and IMF drivers.

2. Current State of the Focused Science Topic

2.1 Scientific Understanding

2.1.1 Ionospheric Transport. The equatorial, mid-latitude, auroral, and polar ionospheric regions are coupled by processes that redistribute cold ionospheric and plasmaspheric plasma throughout the interconnected system. In particular, cold plasma enhancements, created at equatorial and mid-latitudes by stormtime processes, are carried poleward by disturbance electric fields through mid-latitudes to the intense outflow regions located at cusp, auroral, and polar cap latitudes.

The processes that ultimately supply cold, heavy ions of ionospheric origin to the magnetosphere occur in three stages. First, plasma redistribution at low altitudes (< 1000 km) brings cold dense plasma onto flux tubes threading the cusp, polar cap, and auroral acceleration regions. Second, acceleration processes in the cusp and polar cap and at nightside auroral latitudes inject these ionospheric source plasmas outward along magnetic field lines into the magnetotail and outer magnetosphere. Third, magnetospheric processes accelerate and redistribute these previously cold ions in the ring current and plasma sheet.

2.1.2 Magnetospheric Transport. Multipoint plasma and plasma composition measurements in the lobes, plasmasheet and inner magnetosphere reveal significant enhancements of plasma of ionospheric origin during storms. We know from measurements that ionospheric H^+ streams out of the high-latitude ionosphere continuously (outside the plasmasphere proper), regardless of the solar wind interaction, and is powered mainly by the solar EUV energy absorbed in the *F* layer [e.g., *Moore and Horwitz*, 2007]. Auroral processes are embedded within the region of H^+ polar wind, and modify it principally by heating and accelerating the protons without much effect on their escape flux. In contrast, the O^+ plasma is otherwise gravitationally trapped in the *F* region, except where auroral heating and acceleration processes come to bear. The O^+ flux ranges from negligible to many times larger than the polar wind flux, depending strongly on the combination of thermal energy carried into the ionosphere by precipitating hot plasma electrons and electromagnetic power transmitted into the ionosphere from the high-altitude hot plasma motions and fluctuations thereof.

Moreover, we know that the plasmaspheric region represents an accumulated polar wind outflow that has filled the closed flux tubes to pressure equilibrium with gravity, eventually shutting off the outflow. Outside the plasmasphere, the solar wind interaction creates a circulating flow that carries polar wind like plasmas from the outer plasmasphere to the dayside magnetopause, where flux tubes are connected with the solar wind flux tubes and participate in boundary layer flows. When magnetospheric circulation increases as it does during times of strong solar wind coupling, the outer layers of the denser plasmasphere are stripped away and the plasmasphere reduces in size substantially, while this plasma is supplied to the magnetospheric boundary layers, where some fraction of it remains within the magnetosphere and is recycled into the inner magnetosphere, closing the circulation cells.

2.1.3 Magnetosphere-Ionosphere Interaction. Magnetosphere-ionosphere coupling involves the transport of electromagnetic power and mass between the ionosphere-thermosphere and the magnetosphere. The electrodynamic response of the system to changes in solar wind forcing gives rise to changes in convection, in the flow of electrical currents within and between the two regions, and in the dissipation of electromagnetic power, especially in the ionosphere. The inertial interaction involves redistribution of mass and momentum throughout the coupled system and determines, for given solar-wind conditions, the state of convection and current flow. We now recognize that the electrodynamic response is strongly influenced by the inertial response and vice versa, especially for strong solar wind forcing, and that an adequate treatment of the coupling requires a unified approach to modeling [*Lotko*, 2007].

Stormtime enhancements in the solar-wind electric field are observed to cause 1) deep penetration of the enhanced electric field into the magnetosphere-ionosphere system, which, as mentioned in *2.1.1* above, accelerates dense midlatitude plasma of the dayside and entrains it in the high-latitude convection, with the result that 2) substantially elevated parcels of *F*-region plasma enter the cusp, polar cap, and nightside auroral regions. Collisionless plasma acceleration in these regions, fed by enhanced electromagnetic power flows from the solar wind dynamo, diverts large fluxes of convecting ionospheric mass into magnetic field-aligned outflows. Upon reaching the magnetotail, these outflows augment the solar wind population in the plasma sheet. As the energized ionospheric ions join the internal circulation of the plasma sheet come ring current, they are believed to be responsible, in part, for the greatly enhanced stormtime ring current. Numerical studies by *Winglee et al.* [2002], which include the effects of polar wind-like outflows on the magnetosphere while neglecting the effects of feedback on the state of the ionosphere, suggest that the throttled stormtime outflow of heavy ions eventually chokes the storm-enhanced convection by mass loading the magnetosphere. However, ion outflows also augment the plasma density in the low-altitude auroral magnetosphere where the field-aligned currents otherwise tend to be charge-carrier (electron) starved. Thus these outflows effectively increase the local number density and reduce the need for parallel electric fields to maintain current continuity. The net effect is to reduce the energy flux of electrons precipitating in the ionosphere. In this case, theory predicts a reduced ionospheric conductance and a higher transpolar potential relative to what would be expected without this feedback mechanism. Studies of the combined effects of inertial loading of magnetospheric convection by heavy ion outflows and the effects of the outflows on electron precipitation and ionospheric conductance are needed.

2.1.4 Ring Current and Radiation Belt Dynamics. The plasma composition in the near-Earth magnetosphere varies significantly with geomagnetic and solar activity, with H^+ being the dominant ring current ion species during quiet time, and O^+ contributing mostly during active time. During the main phase of moderate geomagnetic storms, the O^+ contribution to the ring current energy density is about 20-30% of the ring current, while for large storms (*Dst* <-250 nT) the O^+ energy density can exceed 50% of the total [*Hamilton et al*, 1988, *Kistler et al.*, 1989]. In addition, the ring current ion distributions become anisotropic and may generate electromagnetic ion cyclotron (EMIC) waves in the equatorial magnetosphere [e.g., *Cornwall*, 1977]. The increase of the pitch angle anisotropy is due to the ion energization by betatron acceleration, as well as to losses by charge exchange and collisions at low altitudes with the dense atmosphere. The generation and propagation of the EMIC waves depend strongly on the presence of both cold (plasmaspheric) and energetic (ring current) heavy ions (mainly He^+ and O^+) in the plasmas [e.g., *Rauch and Roux, 1982*]. Heavy ions can modify the frequencies at which wave growth occurs as well as the growth rates themselves, and may significantly decrease the group velocity. Moreover, the presence of heavy ions results in stop bands above the gyrofrequency of each ion species. Global ring current simulations indicate that intense EMIC waves are excited within regions of spatial overlap of energetic ring current protons and dayside plasmaspheric plumes and along steep density gradients at the plasmapause [e.g., *Jordanova et al.*, 2001]. Pitch angle diffusion caused by resonant ion cyclotron interactions scatters particles toward the loss cone and increases significantly the ion precipitation at low altitudes [e.g., *Sóraas et al.*, 1999; *Jordanova et al.*, 2003]. EMIC waves strongly affect the loss of MeV electrons and the knowledge of their global distribution and power are crucial for the accurate understanding of radiation belt dynamics.

2.2 Observational and Modeling Capabilities

2.2.1 Ionospheric Observations. A variety of observational datasets are available to characterize the redistribution of the source plasmas at ionospheric heights. GPS observations of ionospheric total electron content (TEC) are available since before 2000 for an expanding array of global land-based receiving sites. These data have been collected and processed into global maps depicting the spatial characteristics and temporal evolution of ionospheric TEC. These data are available to support our studies through the MIT Madrigal database. Supplementing the land-based TEC observations are over-water satellite-based TEC observations from the Jason and TOPEX altimeter missions. These data are available through Madrigal.

The redistribution of the ionospheric plasma is closely related to the global convection pattern. High-resolution and synoptic ion drift and auroral boundary-location observations with the DMSP satellites are available at MIT through collaboration with researchers at AFRL. Pass-by-pass survey plots of auroral and ionospheric observations with the DMSP satellites at both high-polar, and low latitudes are pre-processed and available to assist in identifying and interpreting conditions appropriate for the FST's planned investigations.

Incoherent scatter radars (ISRs) provide full-profile (100 – 1000 km) observations of ionospheric parameters in several locations important for these investigations. The source of the SED plumes is at mid/plasmapause latitudes in the evening local time sector. Millstone Hill ISR observations of both ion convection and plasma-parameter profiles are available for case-study investigations of the plasma source characteristics. At cusp and near-cusp latitudes at noon, the new Poker Flat ISR (AMISR) provides direct observations of plasma characteristics in the cusp ion outflow/acceleration region. A program of daily noontime AMISR experiments was begun in early 2008 in support of these investigations. All ISR processed data and survey plots are publicly available through the Madrigal database.

2.2.2 Low-Altitude Magnetospheric Observations. Low altitude polar orbiting spacecraft provide essential measurements of particle and fields at the altitudes were ions of ionospheric origin are accelerated to escape velocities to subsequently populate the magnetosphere. Recently *Strangeway et al.* [2005] developed a set of scaling laws that relate the energy sources that heat the ionosphere to the flux of outflowing ions. The two sources of heating for the ionosphere are Poynting flux, which causes heating of the *E*- and lower *F*-region ions, and the precipitation of soft electrons, which heats the *F*-region electrons. For electron heating, an ambipolar electric field then increases the scale height of the ionosphere. Once the ions have reached higher altitudes other processes, such as ELF or Alfvén wave heating, further energize the ions so that they can escape gravity and provide a plasma source for the magnetosphere. The initial analysis of *Strangeway et al.* [2005] used various plasma moments (e.g., electron energy flux and number flux, ion number flux) to characterize the plasma. These were combined with measurements of the fields (e.g., Poynting flux, integrated wave power) to derive purely empirical scaling laws. While these scaling laws provide a useful first start in deriving scaling laws that can be used to parameterize outflows in global models, the scaling laws need to be extended to include parameters that are more closely tied to theoretical and modeling efforts.

The FAST data cover an entire solar cycle, so other dependencies, such as solar illumination, and solar EUV fluxes can be taken into account. Furthermore, the initial studies were restricted to some 33 orbits acquired in the dayside cusp, which is characterized by a mixture of unaccelerated magnetosheath electrons, wave accelerated electrons and parallel electric field accelerated (inverted-V) electrons. For the nightside, on the other hand, the particle signatures are much more distinct, with wave accelerated electrons being clearly separated from inverted-V electrons. The large extent of data from the FAST spacecraft makes it possible to separate the energy inputs and resultant outflows as a function of not only local time and solar cycle, but even plasma regime (e.g., cusp, inverted-V, or Alfvén-wave dominated acceleration regions). Data are available for all local times.

2.2.3 High-Altitude Magnetospheric Observations. The phenomenology of plasma redistribution in the high-altitude magnetosphere will be investigated using data primarily from the Cluster satellites. Cluster is a 4-spacecraft mission in a 4 R_E x 19 R_E polar orbit, with apogee in the equatorial plane. Cluster is the first satellite mission since ISEE to measure ion composition in the bulk-plasma energy range in the central tail. The Cluster CIS/CODIF data set [*Rème et al.*, 1997] measures full 3D distribution functions for the major ion species over the energy 20 eV to 40 keV. The temporal resolution of 4-16 seconds (depending on mode) for a full 3D distribution function of O^+ is unprecedented in this region (and only duplicated by the similar instruments on FAST and Equator-S). During the first four years of the mission, the plasma sheet encounters occur mainly at Cluster apogee of 19 R_E. In the Cluster extended mission, the spacecraft will be crossing the plasma sheet at progressively closer distances. The O^+ in the lobes and plasma sheet during storm-times is clearly visible in the Cluster/CIS data set. The Cluster measurements can be used both to monitor when the O^+ beams from the cusp are being transported to the near-earth plasma sheet, and the composition of the plasma sheet itself.

2.2.4 Outflow Models. At the present time, there exist several types of models describing the transport of ionospheric plasma along magnetic field lines at high altitudes. Among these models are "fluid-kinetic" codes which describe the lower ionosphere, typically from the *E*-region to the topside, with low-moment fluid-based treatments; the fluid description is then coupled to a generalized semi-kinetic (GSK) or hybrid treatment, which describe the ions kinetically from the topside ionosphere to several earth radii in altitude. The low-moment fluid treatments include comprehensive ionospheric chemistry and ion-electron and energy production and loss processes, while the GSK higher-altitude treatments include Coulomb collisions and collisions between ions and neutrals, as well as incorporation of auroral effects such as transverse ion heating by electrostatic components of presumed low-frequency waves. However, at present they do not directly incorporate the effects of Alfvén wave processes on ions and electrons.

2.2.5 Global MHD Simulations. Single fluid MHD simulations have been reasonably successful in describing the overall structure and dynamics of the solar wind-magnetosphere-ionosphere interaction. These simulations include in an approximate way the electrodynamic coupling between reconnected solar wind plasmas and ionospheric plasmas. This coupling is mediated by electric current systems that dissipate solar wind energy in the ionosphere and, through ion-neutral collisions, in the neutral atmosphere. Because the ionospheric plasma is not allowed to escape the *F* layer in these models, they do not have realistic distributions of plasma within them, and cannot properly assess the dissipation of solar wind energy in high altitude, circulating parts of the ionospheric plasma. We expect that development of multifluid models will open up a new generation of studies in which the real distribution of the ionosphere is taken into proper dynamical account. Four recent developments promise to improve the fidelity of the fields derived from global simulation models.

- Multifluid versions of the LFM and BATSRUS global models are just now becoming available. These models include separate populations of protons and heavy ions of ionospheric origin as well as electrodynamic coupling to the ionosphere. As discussed in the integrated research plan, the multifluid LFM simulations will provide a means of comparing magnetospheric entry of solar wind fluid parcels in the multifluid simulations with the entry of solar wind test particles derived from particle-trajectory calculations. These two complementary approaches should provide insights into results derived from mass-resolved satellite data, e.g. on the dynamics of plasma sheet composition.

- Boundary conditions representing ionospheric outflow have been implemented in the one-fluid version of the LFM model and will be improved upon and implemented in the multifluid LFM (MFLFM) model as part of this TR&T project (see also Sec. *2.2.4* above). We envision comparisons, similar to those for solar wind entry described in the previous bullet, on the transport and fate of ionospheric outflows.
- Electrodynamic coupling between one-fluid versions of the global models and ionosphere-thermosphere general circulation models are now available (LFM-TIEGCM, BATSRUS-GITM, and OpenGGCM-CTIM). These coupled models can be used to study the effects of magnetospheric processes on the state of the ionosphere and vice-versa. As discussed in Sec. 3.5 below, electrodynamic coupling between the MFLFM and the TIEGCM will also be implemented as part of this TR&T project.
- Coupling between one-fluid versions of a global magnetospheric model (LFM and BATS-RUS) and the Rice Convection Model are also available. Although a coupled LFM-RCM model, in principle, would be useful for studying ring current development during storms, as of this writing it is not yet clear that the coupled model is sufficiently robust to simulate storm intervals. At this time we do not envision using the coupled LFM-RCM or BATSRUS-RCM models for this TR&T project; however, the individual contribution described in Sec. 3.3 below will make progress in coupling the RAM ring-current model to the BATSRUS-GITM global model.

2.2.6 Test-Particle Simulations. We have been able to make considerable progress using computations of ionospheric particle motions within the global fields computed by current single-fluid global simulations. In this way, the pathways through which ionospheric ions circulate around the magnetosphere can be assessed, and by weighting particle trajectories with phase space densities, we can estimate the properties of the ionospheric plasma as it circulations. Significantly, this method allows the proper computation of the full adiabatic behavior of ions in regions of gyro-radius scale structures, and when gyro-period scale variations are present. We can thus evaluate some of the physics revealed in hybrid multifluid codes, albeit without the full self-consistency that such codes would possess.

2.2.7 Kinetic Simulations of the Inner Magnetosphere. Kinetic simulations are the optimal tool to study particle dynamics in the inner magnetosphere. The current state-of-the-art of these simulations makes use of fields from either empirical models or global MHD models, e.g., to simulate ring current dynamics during storms. The development of ring current models that calculate self-consistently the electric and magnetic fields in which the particles drift is needed. In addition, the plasma in the inner magnetosphere is anisotropic and may excite plasma waves. To investigate these effects a self-consistent model including particle transport and wave instabilities must be developed.

3. Individual Contributions

3.1 Ionospheric redistribution: Storm enhanced density as a source for ion outflow in the cusp and polar cap (*Foster*)

MIT Haystack Observatory is pursuing a multi-instrument investigation using both ground and space based systems to investigate the characteristics and dynamics of the ionospheric source plasmas in ion outflow/acceleration regions at the base cusp field lines and in the polar cap. An accurate specification of source plasma characteristics is needed to model and understand the injection of ionospheric ions into the magnetosphere during storms. In particular, the MIT project will examine the conditions under which lower-latitude enhanced-density ionospheric plasma is supplied to the ion outflow and acceleration regions, and the conditions under which this material is drawn into the polar cap, forming a polar tongue of ionization (TOI). It will employ a wide range of available ground based [incoherent and coherent scatter radar, Global Positioning System (GPS) receivers] and DMSP in-situ satellite diagnostics. The results of these studies will significantly advance knowledge of the temporal evolution and ultimate impact of stormtime ionospheric restructuring on the source regions providing outflow of heavy ionospheric ions to the magnetosphere.

Dr. John Foster will focus on the effects of sub-auroral electric field (SAPS), ionospheric density/ TEC enhancements (SED, plasmasphere erosion plumes, and ionospheric density gradients), and will coordinate incoherent scatter radar, distributed ground-based instrumentation, and coordinated satellite - ground-based investigations. *Dr. Philip Erickson* will assemble convection velocity and plasma parameters using PolarDARN / SuperDARN HF radars, the NSF incoherent scatter radar network, and Madrigal database tools. Dr. Erickson will also implement any radar operations suggested by the Team as the project progresses. *Dr. Anthea Coster* will oversee GPS TEC analysis activities, including high resolution line of sight slant TEC determinations, incorporation of CHAIN GPS data, and SED/TOI identification. The following are named Collaborators on this MIT project: *Dr. Frederick Rich (AFRL)* will provide access to the DMSP data and analysis software used. *Dr. M. Rouhonomei (JHU/APL)* will be our point of contact for collaborations involving SuperDARN observations and analysis. *Prof. J-P St-Maurice (U Saskatchewan)* will collaborate on the interpretation of Rankin Inlet determinations of polar cap flows and instability processes during TOI events. *Profs. R. Schunk and J. Sojka (Utah State Univ.)* will collaborate on data/model-comparison studies of polar wind outflow from enhanced density structures in the polar ionosphere.

3.2 Auroral I-M plasma transport with Alfvén kinetic effects (*Horwitz*)

In coordination with members of the LWS TR&T T3b team, we will combine analysis of particle, wave and field observations from aboard recent spacecraft sampling the auroral ionosphere-magnetosphere coupling regions, with the coupling of an ionospheric plasma transport model with kinetic effects and a code for simulating the propagation and effects of Alfvén waves on electron energization to synergistically explore key aspects of the physics of the high-latitude ionosphere-magnetosphere region extending from the ionosphere to approximately 1 R_E altitude. The data utilized will include observations from POLAR, FAST, DMSP and other relevant spacecraft. One important outcome expected from this investigation is the distillation of new useful formulas for the ionospheric plasma outflows as functions of the principal drivers of these outflows. These formulas will be designed for convenient use by global magnetospheric modelers.

3.3 A comprehensive self-consistent inner magnetosphere model (*Jordanova*)

We propose to develop a comprehensive model of the inner magnetosphere that will include a kinetic ring current model (RAM) coupled with a 3-D force balance model that calculates self-consistently the magnetic field and inductive electric field, and an MHD model coupled to an ionospheric model that calculates self-consistently the convection electric field. The individual models will be linked together by integrating them into the Space Weather Modeling Framework (SWMF) developed at the University of Michigan. Unique features of all models will thus be combined in obtaining a fully self-consistent inner magnetosphere (IM) model that takes into account the anisotropic plasma distribution. Such anisotropy is critically important for determining the onset of instability for various plasma waves which affect the dynamics of both ring current ions and radiation belt electrons. Our kinetic code treats these wave instability processes self-consistently with the evolving energetic particle populations.

In the coupled model the particle flux at the outer boundary of the simulation will be derived from the output of the MHD model. To this end the fluxes at the outer RAM-SCB boundary will be modeled as Maxwellian distributions using the density and temperature values from the MHD simulation. The ion composition at this outer boundary will be inferred from empirical studies as function of solar and geomagnetic activity [*Young et al.*, 1982; *Roeder et al.*, 2005]. An improved approach will be to collaborate with other teams from this Focus group. More specifically, we will use as boundary conditions the fluxes calculated from the projects led by T. Moore and L. Kistler; these will include both ion composition and pitch angle dependence. We will simulate ring current evolution during the selected FST storm events. The model results will be compared with in situ and ground-based data provided by the other FST projects in order to constrain the free model parameters and validate the predictive capabilities of our model.

3.4 Solar wind drivers of plasma sheet composition (*Kistler*)

The main objective of this work is to determine the solar wind conditions that are most effective in bringing ionospheric plasma into the near-earth plasma sheet. Earlier work has shown that it is mainly during storm-times that O+ is a major constituent of the plasma sheet, but there is a considerable variability between storms. The O+ in the plasma sheet can come from direct injection from the nightside aurora and outflow from the dayside cusp, and the conditions which drive these two source regions and control their transport into the plasma sheet may be different. Ultimately, this work should help in the specification and forecasting of the plasma sheet composition, as well as in understanding the energization, transport and loss of ionospheric ions.

Methods and Techniques: The project will be a combination of case studies and a statistical approach to when, where and under what conditions O+ is observed. The polar CLUSTER orbit is ideal for both monitoring when the O+ beams from the cusp are being transported to the near-earth plasma sheet, and when enhanced O+ is observed in the plasma sheet itself. As a first step, we will identify a few key storms with different solar wind drivers and good CLUSTER coverage to determine how the lobe and plasma sheet composition changes with time. For example we will choose an event which show large dynamic pressure changes and contrast that with an event with little dynamic pressure change, but a large change in B_z. We will compare plasma sheet encounters before the start of a storm, during a storm and in the recovery phase to track the changes in plasma sheet composition and cusp outflow transport during the storm. The results of these initial case studies will be used to identify the trends which can then be confirmed or refuted using a larger statistical study. The other projects mesh with this project in a number of ways. Contributions from other members of the team will help both in better specifying and understanding outflow at the ionospheric level, and in connecting the ionospheric outflow with the plasma sheet observations through modeling.

Using the case studies as a guide, we will perform a statistical study on when and where the O+ beams are observed over the polar cap, in the lobe and in the plasma sheet to determine the transport paths under different conditions, and when the plasma sheet composition increases during the storm. Again, comparisons with ion outflow and particle transport models will be critical to understand the transport of the ions and the interplay between dayside and nightside outflow process.

3.5 Effects of stormtime plasma redistribution on M-I coupling (*Lotko*)

The Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) global simulation model will be used to determine how stormtime ionospheric outflows influence 1) the convective transport of ionospheric plasma at auroral and polar latitudes, 2) the distribution and intensity of field-aligned currents at the ionosphere, and 3) the distribution and dynamics of the ionospheric conductivity and Joule dissipation. CMIT integrates the Lyon-Fedder-Mobarry (LFM) global magnetospheric model with the NCAR Thermosphere-Ionosphere Nested Grid (TING) model. This project takes an important step in modeling the magnetospheric and ionospheric-thermospheric regions as a single connected system by including both electrodynamic and inertial couplings between the regions. To this end, we will utilize and advance a recently implemented, multifluid version of the LFM component of CMIT. Proposed extensions to the CMIT model also include causally driven cusp-region, auroral/polar-cap boundary-region, and polar-wind outflows at LFM’s ionospheric boundary, regulated by TING’s dynamic specification of the ionosphere. This investigation is directly aligned with the goals of LWS TR&T Focused Science Topic b) Effects of Ionospheric-Magnetospheric Plasma Redistribution on Storms. The results will provide a useful touchstone for interpreting measurements, especially mass composition measurements, from existing NASA satellite missions such as Polar and Cluster, and it anticipates future needs to interpret distributed measurements of ionospheric and magnetospheric dynamics from the imminent THEMIS and TWINS missions, the LWS Radiation Belt and IT Storm Probes, and the GEC and MMS satellites.

3.6 Stormtime plasma redistribution processes and consequences (*Moore*)

We propose to establish how ionospheric plasma expansion into the magnetosphere during storms is altered by storm energy flows, and how this expansion influences the dynamics and coupling of the solar wind, magnetosphere and ionosphere to create these storms. Emphasis will be on the plasma and geomagnetic field conditions of the inner magnetosphere, as distorted by the ring current, with the evolution of the ionospheric conductance, temperature and densities. Measures of success include the identification of principal features of plasma redistribution and a quantitative assessment of their impacts over the range of storm-time conditions resulting from solar wind and IMF drivers.

Our specific objectives are to: i) assimilate published observations into a developing model of the expansion of the ionosphere into the magnetosphere, in response to energy inputs from the solar wind; ii) assess and simulate the entry and circulation of solar wind plasmas within the magnetosphere, including the inner magnetosphere. iii) specify and forecast plasmasheet and ring current composition, energy and spatial distribution for representative storm-time conditions, based on the detailed distribution and rate of magnetospheric intake of solar, ionospheric, and plasmaspheric plasmas during storm conditions; iv) assess the impacts of storm-time ionospheric and plasmaspheric redistribution and expansion on magnetosphere-ionosphere coupling, including energization, transport, and loss of ionospheric plasmas from the magnetosphere and Earth.

The proposed funding will support a team effort including theoretical analysis, assimilation of observational results including empirical-statistical models based on both space borne and ground based data sets, in support of global modeling of the coupled solar wind, ionosphere and magnetosphere. We will investigate the ionospheric processes relevant to its expansion into the magnetosphere, and the influence of specific physical effects imposed on the ionosphere by the magnetosphere, on the local rates of outflow into the magnetosphere. We will investigate the consequences and impacts of magnetospheric intake of plasma from all sources. We will compare our results with relevant data sets from of the Heliophysics Great Observatory to validate the dynamic local response of source regions to solar wind influences and the simulated characteristics of the magnetospheric circulation. Empirical comparisons will improve and validate our simulation results, leading the way toward improved global circulation models of geospace and its response to the dynamic heliosphere. Data sets to be used will include, but not be limited to, those from ACE, Wind, and Geotail missions to establish external drivers of the magnetospheric system; published and new data from Polar, FAST, DMSP, and other LEO missions to establish the spatial distribution and rate of ionospheric expansion; and data from the Polar, IMAGE, Cluster, and DoE geosynchronous missions to make contact with magnetospheric responses.

3.7 Ionospheric plasma outflow scaling laws as a function of solar cycle (*Strangeway*)

We propose to extend the database used by Strangeway et al. [2005] to derive the outflow scaling laws to cover the entire FAST mission. FAST was launched on August 21, 1996, and has acquired data for over 11 years, with roughly 30 minutes of data acquired per orbit (except for the fluxgate magnetometer, which usually acquires data over the entire orbit). By extending the database beyond that used by Strangeway et al. [2005] we will answer the following questions: What is the role of Alfvén waves in driving outflows? Can we develop better scaling laws that provide both upper and lower limits that may be a function of solar cycle and ionospheric illumination? Do we need to further divide such scaling laws into morphologically distinct regions (e.g., cusp, invert-V aurora, return currents, and Alfvén aurora)? Can we obtain additional physical understanding of outflows through more refined analysis of the FAST data?

We are proposing to extend the database in a multi-stage process. First we will perform a pilot study, extending the September 24/25 1998 interval to about a month of data. This will allow us to refine the data products and also design additional data products and binning strategies for use with the more extensive database. The second stage will extend the database to the first 20,000 orbits of FAST, since this is the nominal interval over which the DC portion of the electric field experiment was fully operational. The electric field is required to determine the Poynting flux. The third year effort will extend the database to the entire mission. Although we will not be able to continue the investigation of Poynting flux control into this interval, we will be able to at least map outflows over nearly a full solar cycle, and assess the solar-cycle dependent variability electron precipitation driven outflows. Anticipated data products include the following: magnetic field perturbation, along-track electric field, quasi-static Poynting flux, "Alfvénic" Poynting flux, electron moments (density, number flux, energy flux), ion number flux, and ion energy. Other data products may be defined as a result of the pilot study, and consultation with the members of the Focused Research Team.

Throughout the project case studies will be performed. The case studies will be chosen so as to elucidate the results obtained by the statistical analyses, on the one hand, and to guide the choices in how to subdivide the database into meaningful subsets, on the other. In these case studies we will take advantage of resources such as the NASA-sponsored Community Coordinated Modeling Center (CCMC), which provides a "run-on-request" facility for scheduling runs of a variety of heliophysical models, including global simulations of the terrestrial magnetosphere. The global simulations provide an important global context for the in situ observations made by FAST. As a consequence of the proposed work we will also be able to provide suggestions to the CCMC and model developers for additional diagnostics that would be useful for generating maps of outflows as a prediction of the codes.

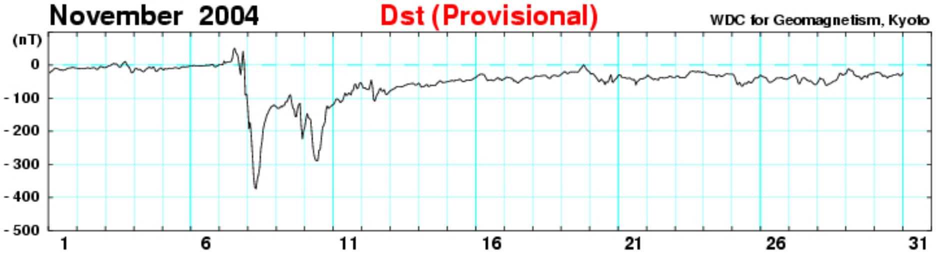
4. Integrated Research Plan

The Integrated Research Plan includes two types of investigations: (A) Two storm events to be investigated by all team members, and (B) special focus studies that draw on the expertise of two or more team members in advancing model development and scientific understanding in areas of direct relevance to the focused science topic. The latter studies will also examine selected storm events for which the available data can be brought to bear more directly on the specific objectives of the special study. The two storm events for general team study will be investigated in concert with the 2006 LWS TR&T Team with focus on "Storm Effects on the Electrodynamics and the Mid- and Low-Latitude Ionosphere." Although the logistics and specific science objectives for a joint meeting are not yet decided, we envision holding the workshop sometime in the third quarter of 2008 for purposes of developing a more comprehensive understanding of the storms.

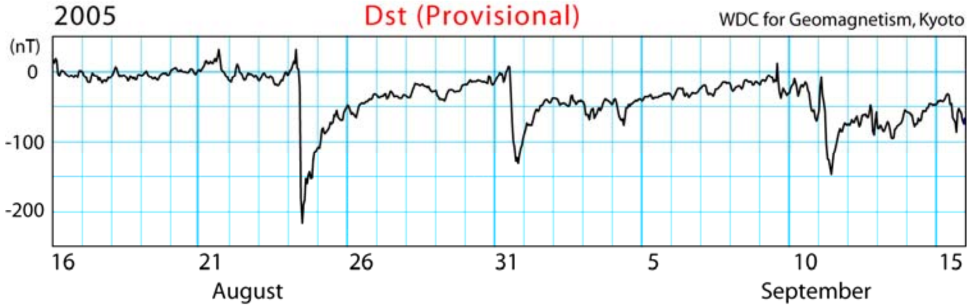
4.1 Team Project: Characterize plasma redistribution during a weak storm and a superstorm using the full complement of data and models available to the team

Description: The study will focus on the 7-12 Nov 2004 superstorm (*Dst* ≈ -380 nT on 8 Nov) and the 31 Aug 2005 moderate storm (*Dst* ≈ -130 nT). The *Dst* context for both storms is shown in the World Data Center plots included below. Data sets to be analyzed for both events include ISR, SuperDARN (as available), TEC and DMSP to characterize the ionosphere, FAST and Polar to characterize the low- to mid-altitude magnetosphere, and Cluster to characterize the plasmasheet and lobe regions. Outflows will be examined using the DyFK model. Global feature of the storms will be examined using the LFM and MFLFM models in concert with particle-trajectory calculations. The development of the ring current and radiation belts will be studied with the RAM code.

7-12 Nov 2004 superstorm. The state of the ionosphere during this storm interval is already the focus of a special issue under development for JASTP and the analysis and results described in those papers will provide useful context for the team study. The initial storm surges evidently removed a substantial amount of plasmaspheric plasma. GPS TEC maps at 0200 UT on 08 Nov 2004 show a strong SED plume entering polar latitudes over the mid-Pacific. Further intensifications later in the day, e.g. 2100-2200 UT, involved significantly-depleted low-latitude source regions. A brief "puff" of SED traversed the cusp around 2200 UT on Nov 8 over central Canada as seen in preliminary TEC maps. Several ISRs operated throughout this interval, and Millstone Hill was in a full "storm-coverage" mode for the events on Nov 8. Cluster and Polar satellite data are available. FAST data from the southern hemisphere are also available.



31 Aug 1005 storm. The Millstone Hill ISR was operating for only 5 hours in midday in a local calibration mode (a 30-day World Day experiment began on Sep 1). A quick survey of on-line data resources for the event shows *Kp* going above 5 around 2000 UT - a time favorable for SED enhancements in the American sector. GPS TEC maps show a weak, but pronounced SED plume entering polar latitudes during the event, so this case appears to be a "lesser-intensity" complementary example to the superstorm. DMSP passes clearly show the development of the strong SAPS plasma velocities needed to carry lower-latitude plasma to cusp field lines. Cluster and Polar satellite data are available. FAST data from the southern hemisphere are also available.



Schedule: Preliminary data analysis and simulation results will be presented at the joint workshop with the TR&T team focusing on "Storm Effects on the Electrodynamics and the Mid- and Low-Latitude Ionosphere" proposed to be held in Boulder sometime in the third quarter of 2008. We anticipate refinements in analysis and development of papers describing these studies during the second year of funding.

Milestones: a) Comparative studies of the ionospheric state diagnosed by radars, TEC and low-altitude satellites and predicted by the CMIT model including evolution of the ionospheric conductance, temperature and densities, transpolar potential distribution, field-aligned currents, electron precipitation, outflow fluence, and Poynting flux impinging on the high-latitude ionosphere (*Foster, Horwitz, Lotko, Strangeway*). b) Description of inner magnetospheric plasma, ring current, B-Field evolution (*Jordanova, Moore*). c) Comparative analysis of plasma transport from low-altitude throughout the magnetosphere (*Foster, Horwitz, Jordanova, Kistler, Lotko, Moore, Strangeway*).

Deleverables: Publications describing team analysis of the events, possibly a special issue or special section of JASTP or JGR. Archived data aggregations and simulations of the events.

4.2 Special Study Projects

4.2.1 Determine the physical processes that regulate auroral- and cusp-region outflows from F-region up to low-altitude boundary of global models (Foster, Horwitz, Lotko, Strangeway)

Description: Plasma redistribution at low altitudes (< 1000km) brings cold dense plasma onto field lines threading the cusp where acceleration processes inject these ionospheric source plasmas outwards along magnetic field lines into the magnetotail and outer magnetosphere. Events will be identified in which significant ionospheric enhancement occurs on cusp field lines (Foster) and for which higher-altitude satellite observations (Strangeway) of plasma acceleration are available. Modeling studies will be performed (Horwitz) to determine the contribution of the enhanced source plasma to ion outflow on cusp field lines.

Schedule: A preliminary simulation of the potential effect of SED-type enhanced ionospheric density structures entering and supplying the Cleft Ion Fountain has been performed and published [*Zeng and Horwitz*, 2008]. In this case, a full plasmaspheric flux tube was allowed to open and transit a zone of transverse ion heating, as would be expected in the cleft region. The results indicate that SED can indeed supply such transverse heating regions, causing bursts of outflows (e.g., over 10^8 O^+/cm^2-sec) to ensue in a region nominally identified as the source of the Cleft Ion Fountain. The effect occurs even in the (artificial) absence of ionizing soft electron precipitation. Appropriate events with ionospheric enhancements and FAST satelite observations are being determined in early 2008 (Foster, Strangeway). Events appropriate for study using Poker Flat ISR cusp-region observations in 2008 and beyond will be identified and examined (Foster, Strangeway).

Milestones: a) feasibility study - modeling - completed. b) intervals for detailed study identified. c) detailed data intercomparison and selection of event study. d) model/data inter-analysis to address cause of effects observed.

Deliverables: A list of events appropriate for further analysis will be prepared for use by the Team. Results of case study comparisons will be published . Model including appropriate cusp-region ionospheric characteristics will be produced to incorporate significant features observed.

4.2.2 Building on results from Project 1, develop lumped-system models and/or parameterizations leading to simple transport models of outflow fluxes causally regulated by driver inputs available from global simulation models. (Horwitz, Lotko, Moore, Strangeway)

Methodology: Develop empirical relations based on FAST data and DyFK model results that connect causal drivers (e.g. bandpass filtered Poynting flux, electron precipitation, solar illumination, etc) to characteristics of the ionospheric outflow (e.g. composition, ion number flux, bulk velocity, thermal energy, anisotropy, e.g., *Bouhram et al*., 2004). These relations will provide boundary conditions and/or ion flux sources for MFLFM simulations.

Description: The current state of global magnetospheric modeling efforts is such that there is great interest in accurately incorporating ionospheric outflows as magnetospheric plasma sources, and that the increasingly sophisticated use of Global Kinetic (GK) approaches as well as the near-term evolution of multi-fluid treatment in MHD codes now allows incorporation of some codification of ionospheric outflows as plasma source inputs. Similarly, there have been recent initial efforts, both data- and theory/simulation-based, to develop simple parameterizations of ionospheric outflow parameters as related to anticipated causal driver values, such as electron precipitation characteristics and wave levels and/or Poynting flux measures. The objective of this project is to advance these parameterizations to provide relatively simple and physically adequate characterizations of the ionospheric outflows at the low-altitude boundary of the global simulations (currently typically 2 R_E geocentric). We intend to pursue development of these new parameterizations on the data side by 1) including more measurements from FAST and POLAR observations, 2) exploring and implementing as appropriate multi-parameter fits or relationships to proposed driver characteristics, and 3) distinguishing AC and DC based Poynting flux measures as separate potential drivers and perhaps other fluxes such as electron precipitation. On the theory/simulation side, we will be pursuing a variety of improvements to the Dynamic Fluid Kinetic (DyFK) model description of the driven ionospheric outflows, including seeking to incorporate Alfvén wave effects on both ion and electron heating, and to seek improved connections with parameters contained in somewhat direct forms in the global magnetospheric models, such as the Poynting flux. We will coordinate the data and theory/simulation efforts such that, ideally, they are consistent with each other to the extent possible, and improvement ideas for each emerge through cross-pollination of the theory/simulation and data analysis work. In particular, the *in situ* parameterization studies will be extended to include appropriate variables more closely tied to the parameters required as inputs or predicted as outputs from the DyFK model. For example, in addition to ion outflow flux, we may include outflow density, since the latter is a predicted quantity from the DyFK model. Close coordination and interaction will also be done with the global magnetospheric modelers so that the representations are suitable for their needs and may be incorporated readily and productively.

Schedule/Milestones:

Year 1

- *Data:* Seek to obtain scaling expressions of outflow densities, flow velocities and temperatures as driven by appropriate driver parameters associated with electron precipitation, Poynting fluxes, ELF wave spectra, etc.
- *Theory/simulation:* Seek to obtain similar but physical parameterizations based on simulations of individual species (H^+, O^+) that specify densities, flow velocities, and temperatures as functions of parameters of soft electron precipitation, ELF waves, solar zenith angle, etc. Initiate efforts to link (at least heuristically) ion wave-driven heating with propagating Alfvén waves and general DC Poynting fluxes as available from global magnetospheric models. Initiate project to couple Alfvén wave propagation and electron acceleration codes to DyFK models for ionospheric plasma transport.
- *Data-Theory comparisons:* Initiation of comparisons between data-based and theory/simulation parameterizations and initial incorporation of these representations into global magnetospheric models.

Year 2

- *Data:* Extension of the ion outflow database to include more intervals, allowing for solar illumination effects to be considered. Addition of other parameters to allow for closer linkage between the DyFK model and the outflow database.

- *Theory/simulation:* Initial establishment of processes by which Alfvén waves lead to ion and electron energization, in part by incorporating Alfvén wave codes into use with DyFK model. Continuation of development of simulation physics based expressions for outflows; initial coupling of these as ionospheric suppliers to global magnetospheric multi-fluid models and iteration with those global models to stimulate further desired improvements in ionospheric outflow expressions formulation.
- *Data-Theory comparisons:* Advancement of intercomparisons between data-based and theory/simulation parameterizations and incorporation of these representations into global magnetospheric models.

Year 3

- *Data:* Completion of the outflow database to encompass as much of the available spacecraft data as possible. This should allow for investigation of solar-cycle effects.
- *Theory/simulation:* Polishing of theory/simulation-based outflow parameterizations based on physics advancement during years 1 and 2. Melding of relatively polished data- and theory/simulation-based outflow parameterizations and incorporation of these representations into global magnetospheric models. Initial comprehensive investigations of the response of global magnetospheric models to such ionospheric sources, and eliciting of physics of ionospheric plasma effects on magnetospheric dynamics.

Deliverables: The study will culminate with a number of science presentations and publications in refereed journals at the completion of this project.

4.2.3 Investigate the low-altitude conditions during events when ion beams of ionospheric origin are observed in the lobes and plasmasheet. (Foster, Kistler, Moore, Strangeway)

Description: Using CLUSTER data, we will choose time periods when clear increases in O^+ beams over the polar cap and in the lobe are observed. A survey of available ionospheric datasets will be performed at these times. We will then determine whether clear changes in low-altitude conditions are associated with the observations of the ion beams. We will also check FAST data for observations of upflow above the ionosphere. Events will be interpreted in terms of the evolution of SAPS electric fields and the transport of low-latitude plasma onto field lines associated with cusp-region plasma acceleration.

Schedule: Identify candidate events. Determine whether the required ionospheric data is available, and whether FAST data is available. Select and analyze representative case study (2008)

Milestones: a) List of events prepared; b) ionospheric characteristics identified; c) condition and recent history of lower-latitude ionosphere redistribution examined.

Deliverables: List of events for which appropriate datasets are available. Published results.

4.2.4 Determine how the plasmasheet distribution and composition change during a storm and for different solar wind drivers. (Jordanova, Kistler, Lotko, Moore)

Description: Vlasov simulations of the inner magnetosphere that incorporate important kinetic processes require a boundary condition to be specified in mid-magnetosphere, which should be tied to solar wind conditions. A magnetofluid global simulation provides an ideal way to specify this boundary condition from solar wind conditions, but does not provide for ionospheric plasma sources that respond to the solar wind and supply plasmas to the inner magnetosphere. Essentially, we seek to develop parameterizations of the distribution and composition of near-earth plasmasheet ions for use in ring-current models. Empirical relations and/or specific event results would be derived from plasmasheet satellite data and/or Global Ion Kinetic (GIK) simulations. Achieving this goal will require an extensive statistical study of the near-earth plasma sheet to be correlated with simulations of the plasma sheet over the same range of conditions. This study will be part of the results from statistical studies performed using the available data.

We propose to establish how ionospheric plasma expansion into the magnetosphere during storms is altered by storm energy flows, and how this expansion influences the dynamics and coupling of the solar wind, magnetosphere and ionosphere to create these storms. Emphasis will be on the plasma and geomagnetic field conditions of the plasma sheet, as boundary conditions for inner magnetosphere simulations. Measures of success include the identification of principal features of plasma redistribution and a quantitative assessment of their impacts over the range of storm-time conditions resulting from solar wind and IMF drivers.

Schedule/Milestones: The following progression is planned toward these goals.

CY2007

- Complete and publish the study of solar, polar and auroral wind response to the 20-21 Nov 2003 superstorm.
- Develop the tools with which to initiate plasmaspheric wind trajectories on the outer boundary of the CRCM based on plasmaspheric plumes generated by the embedded Ober plasmasphere.
- Seek to use a global circulation model that will accept inflows from the ionosphere according to our current empirical scalings or updates of them, as appropriate.
- Simulate and publish the effect of sawtooth or periodic substorm events in the magnetotail, using empirical fields with well-known characteristics.

CY2008

- Add plasmaspheric plume simulations to the 20-21 Nov 2003 super-storm simulation and publish the results.
- Seek a global simulation with an embedded dayside reconnection module based on a full PIC simulation of the effects of inflow density and temperature on reconnection rate and dynamics.
- Select, simulate, and publish additional well-observed geospace storm events across the spectrum of size and phenomenology, containing intervals of steady convection, isolated substorms, and sawtooth or periodic substorms.

CY2009

- Determine and publish the effects of plasmaspheric plumes on magnetospheric convection via loading of dayside reconnection.
- Select, simulate and publish additional well-observed events, filling out the spectrum of size and phenomenology, and testing against relevant published data sets.
- Investigate the feasibility of, and if possible, develop a real time magnetospheric model that accounts for all known plasma redistribution effects during geospace storms.

4.2.5 Determine how plasmasheet distributions and composition influence the ring current, inner magnetospheric plasma, and B-field distributions. (Jordanova, Kistler, Moore)

Description: It has been established that the plasmasheet and ring current ion fluxes can be dominated by O^+ ions and that they become anisotropic during storm times and may be unstable to wave excitation. However, the spatial and temporal variations of the fluxes, as well as their dependence on geomagnetic activity are not well known. To investigate this dependence, we will use the coupled inner magnetosphere model described above in 3.3 to simulate the stormtime ring current dynamics, employing as boundary conditions the plasmasheet fluxes derived from the particle-trajectory calculations described in 3.6 or satellite data as described in 3.4. We will study how ring current morphology, energy density, B-field distributions, and EMIC wave growth are affected by ion composition and anisotropy changes during main and recovery storm phases.

Schedule: Select storms for detailed study. Simulate ring current dynamics during the selected storms with the RAM code using the fluxes from particle tracing routines and/or satellite data as boundary conditions. Compare the results with other codes and satellite data.

Milestones: a) Prepare the boundary conditions for the selected events. b) Perform one-way coupling of the RAM code with the MHD code. c) Obtain a two-way coupled MHD-RAM code.

Deliverables: Obtain global patterns of B field distribution, EMIC waves, and ion and electron precipitation as function of storm-time. Publish the results regularly in peer-reviewed scientific journals.

5. Anticipated State of the FST at the Conclusion of the Project

At the conclusion of the project, we anticipate the following advances in scientific understanding of ionospheric-magnetospheric plasma redistribution during storms and in our capabilities to model these events:

- Confirmation of role and impact of enhanced SED ionization at *F*-region heights on cusp field lines in enhancing heavy ion injection into magnetotail;
- Determination of the principal drivers of ionospheric outflows including the role of Alfvén waves;
- Development of “scaling law” representations of ionospheric outflows in terms of causal drivers, including electromagnetic power and electron precipitation characteristics;
- Incorporation of lumped transport models of causally driven ionospheric outflows into global ionospheric-magnetospheric models;
- Evaluation of the role of different types of ionospheric outflows in global magnetospheric dynamics, and of the feedback of magnetospheric changes on the dynamic state of the ionosphere for various solar-wind drivers and magnetospheric conditions;
- Clarification of the relationship of the occurrence of lobe ion beams to the the occurrence of ionospheric redistribution events and their effects on ionospheric outflow and transport;
- Determination of changes in the state of the plasmasheet including ion composition over the course of a storm and how these changes influence the ring current and the boundary conditions used to drive ring current models;
- Development of an improved inner magnetospheric model that will feature explicit inclusion of all relevant ion species, anisotropic particle treatment, and self-consistent calculation of the magnetic and electric fields; and

- Evaluation of the effects of anisotropic pressure and O^+ ion composition on ring current dynamics, EMIC wave growth, and the inner magnetospheric B-field distribution.

Appendix

This appendix tabulates candidate storm events and their various attributes as discussed at the Aug 2007 and Mar 2008 team meetings. For reference a catalog of 79 storms is also available at http://cdaw.gsfc.nasa.gov/geomag_cdaw/Data_master_table.html. Some criteria for selection of relevant events include: a) preliminary studies have already been undertaken by various team members; b) range of storm intensities – moderate and major – and different solar wind drivers, e.g. CMEs and high-speed streams; c) data availability; d) overlapping data sets – 1 or 2 before 2000 when the full suite of FAST were available, Cluster after 2002, TEC after 2001; and e) up-stream solar wind data are available to drive CMIT and MFLFM.

Candidate events proposed for consideration at the August 2007 team meeting include (IMED indicates under consideration by the some members of the TR&T team on "Storm Effects on the Electrodynamics and the Mid- and Low-Latitude Ionosphere:"

- 23-26 Sep 1998 (Mike, Bob, John) CME-driven
- 31 Mar 2001 (IMED)
- 11 Apr 2001 (IMED)
- 18 Apr 2002 (IMED)
- 1 Oct 2002 (Lynn)
- 23 Oct 2002 (Lynn, Vania) High-speed stream
- 29-30 Oct 2003 (IMED)
- 20 Nov 2003 (IMED)
- 24 Aug 2005 (Lynn)
- Neither IMAGE nor Cluster data are available for the Sep 1998 event.

MIT studies of major events of potential interest to the FST topic include:

- 25 Sep 1998: ISR World Day experiment with interesting SAPS/SAID activity. Wave processes within SAPS channel (Mishin papers). No GPS TEC readily available.
- 31 March 2001: extensive GPS TEC analysis with IMAGE EUV coverage. TIM modeling studies performed on this day. Plume enters polar cap via cusp over Alaska.
- 11 April 2001: extensive GPS TEC analysis with IMAGE EUV coverage and Millstone Hill ISR obsevations of the flux of ions carriend into the cusp/cleft region (204 paper written on cusp-ionosphere SED flux). High-density SED depostied into cusp ion outflow region.
- 29 and 30 October, 2003: extensive GPS TEC analysis with DMSP overflights. Very-high density TEC over US and Canada and into conjugate polar regions.
- 20 November 2003: extensive GPS TEC analysis, distributed ISR observations in the cusp and polar cap, with DMSP overflights. (paper written on polar TOI formed in coupled process). Strong conjugate TEC enhancements in cusp ion outflow region.
- 18 April 2002: GPS TEC, ISR World Day, and DMSP coverage.

Lynn Kistler notes that the following events have good Cluster data showing enhancements of O^+. Most are preceded by a pressure increase in the solar wind. The amount of southward B_z varies considerably.

- Sept 7, 2002 (min Dst -181)
- Sept 30, 2002 – small storm, but good Cluster data, clear signatures
- Aug 18-19, 2002 – First of three decreases in *Dst*.
- Oct 1-2, 2002 – Big storm, nice rotation in B_z, probably CME
- Oct 23, 2002 – Smaller storm. Identified as a high speed stream. Mei-Ching Fok has already done some work on this.
- Aug 17-18, 2003 – Nice big storm
- Aug 24, 2005– Nice big storm

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