Heliophysics Living With a Star Science
Abstracts of selected proposals
(NNH18ZDA001N-ROSES)

Below are the abstracts of proposals selected for funding for the Heliophysics Living With a Star Science 2018 program. The abstracts are listed by Principal Investigator (PI) name and include institution and proposal title. One hundred and four full proposals were received in response to this opportunity. On October 4th, 2019, twenty-eight proposals were selected for funding.

Oleksiy Agapitov/University of California, Berkeley
The Response of Inner Magnetosphere Wave-Particle Interaction Regime and Efficiency to Solar Wind Parameters

The Earth's radiation belts present a natural space hazard to space exploration. Energetic particles cause single-event upsets and deep dielectric charging in spacecraft electronics and may be harmful to humans in space. Although the past several years have seen a great progress in understanding the processes that drive radiation belt dynamics, and much data has been collected by missions such as the Van Allen Probes empirical models are still the best approach to the modeling of the electron flux dynamics.
We propose a new model of energetic electron diffusion rates based on the VLF measurements in the radiation belts by the NASA missions DE1, CRRES, Polar, Cluster, THEMIS, and Van Allen Probes covering three solar cycles (from 1981 to 2018 with a gap in 1990s) and the most comprehensive approach to calculation of the diffusion coefficients (taking into account wave normal angle distribution, wave intensity at off-equatorial regions, and the local plasma density) to evaluate how the dynamics of solar wind affect the transport, acceleration and loss mechanisms of the inner magnetosphere radiation environment. Also, we will develop the patch of the model extending its applicability to the extremely perturbed parameters of solar wind through the special processing of the highest observed geomagnetic storms (DE1 and Cluster measurements) as well as the most powerful storms from the Van Allen Probe mission (with Cluster and THEMIS data)
Science Objectives:
1. Development of the empirical model of the VLF activity in the inner magnetosphere on the solar wind parameters;
2. Calculating and parametrization the wave-particle interaction efficiency under the quasi-linear approximation;
3. Extending the model to the highest observed solar wind parameters;
4. Validation of the model on the available spacecraft VLF data in the statistical pattern, on the intense geomagnetic storm case studies, and investigation of scaling possibility to the extreme geomagnetic events.
Methodology is based on the multi missions VLF spectral matrices and waveform analysis (amplitude distribution, wave normal distribution); the wave parameters database development (including the location and solar wind parameters); statistical processing of

the database (to determine the key correlations); numerical calculations of the scattering and acceleration rated under the quasilinear approximation; statistical analysis of the model remains for validation of the model (case studies and statistical processing with the spacecraft data comparison).
Relevance to the LWS FST: The proposed study will evaluate the response of the efficiency of wave-particle interaction in the inner magnetosphere to the solar wind parameters providing the empirical model for the wave-particle scattering and acceleration rates, validation of the model (evaluating the applicability limitations) with the available spacecraft data, thus, will contribute to the FST topic Understanding the Response of Magnetospheric Plasma Populations to Solar Wind Structures . The expected impacts would be to LWS-TRT Strategic Science Areas SSA-0 SSA-1 and SSA-6.
The proposed model, based on the all available VLF spacecraft measurements (covering 3 solar cycles) and taking into account the recent findings in wave-particle interactions physics will be a necessary component for the models of the magnetosphere dynamics and a valuable part of the Focused Science Team effort. The global models of the magnetosphere dynamics driven by the solar wind include wave-particle interactions as a significant part responsible for seed (50-100 keV) and core (subrelativistic and relativistic) electron populations in the inner magnetosphere. The existing wave models are too simplified (the output is wave amplitude without latitude dependence, wave normal angle distribution, plasma density model) and limited by weakly perturbed conditions (Kp<7), thus cannot be extended to the extreme events.

Phillip Anderson/University Of Texas, Dallas
Response of the Ionosphere and Thermosphere to Geomagnetic Storms in the Mid to Low Latitudes

The purpose of the proposed research is to understand how energy is transferred from the high-latitudes to mid and low latitudes during geomagnetic storms and how this energy impacts the ionospheric structure and the occurrence of radiowave scintillation. It will address FST #1, namely Mid-latitude and Equatorial Dynamics of the Ionosphere-Thermosphere System . In particular, the research will focus on the generation and propagation of acoustic gravity waves (AGWs) produced in the auroral region and the associated traveling atmospheric and ionospheric distrubances (TADs/TIDs), their impact on ionospheric structure in the mid and low latitude, and their impact on the generation of the ionospheric bubbles responsible for ionospheric scintillation. We will use ionospheric data from the C/NOFS and DMSP satellites, thermospheric data from the CHAMP, GRACE, and GOCE satellites, a globally distributed set of TEC measurements from ground-based GPS receivers, along with the Global Ionosphere Thermosphere Model (GITM). With the given set of measurements, we will cover nearly the entire realm of interest of the thermosphere/ionosphere system, although other datasets such as ionosonde networks, radars, and imagers will be considered.
The presence of TIDs and their characteristics (wavelength, propagation speed, orientation, etc&) will be determined by the GPS measurements. The DMSP and C/NOFS data will be used as a complement to the GPS measurements and will also be

used to determine the TID characteristics, filling in where the GPS measurements are not available. The CHAMP, GRACE, and GOCE thermospheric data will, in the same way, be used to determine the characteristics of the TADs associated with the TIDs. Finally, GITM simulations, bounded by the measured thermospheric and ionospheric parameters will be used to tie the measurements together and provide a global picture of the propagation and structure of the TADs/TIDs and the response of the ionosphere. The high latitude inputs to the GTIM model will be bounded by the DMSP ion drifts, responsible for Joule heating, and precipitating particle responsible for particle heating.
With the given set of measurements, we will cover nearly the entire realm of interest of the thermosphere/ionosphere system. Specific questions to be addressed are:
1) How is the propagation and structure of TADs/TIDs dependent on longitude?
2) What are the effects of TIDs on the generation of the ionospheric bubbles responsible for radiowave scintillation, what are the important associated TID characteristics (wavelength, speed, orientiation, etc&) and what is the impact of longitude (geomagnetic field orientation)?
3) What is the impact of geomagnetic activity and TADs/TIDs on ionospheric structure in the mid and low latitudes and how does the response of the ionosphere in these regions depend on longitude?
These questions clearly address the questions and goals of the FST "Ion-Neutral Interactions in the Topside Ionosphere". In particular, the following science questions listed in the solicitation:
"	What is the mid-, low-, and equatorial latitude structure of plasma density, particularly during geomagnetically active periods, and how does the magnetic field longitudinal orientation and magnitude affect it?
"	What is the role of TIDs and TADs?
"	How does the coupling between lower atmosphere and ionosphere (possibly source for non-migrating tides and localized gravity wave activity) contribute and affect TEC and scintillation?
The proposed study clearly addresses the type of investigations sought, using historical, ongoing and future observations from space and ground instrumentation in combination with a physics based model, and addressing several of the required science questions.

Jean Berchem/University of California, Los Angeles
Kinetic modeling of the impact of solar wind structures on the dayside magnetosphere

We propose to use large-scale implicit particle-in-cell (PIC) simulations embedded in global magnetohydrodynamic (MHD) simulations to improve our understanding of the response of the dayside magnetosphere to the impact of solar wind structures. The main science objectives of the study will be to investigate how these structures affect kinetic processes at the magnetopause and how this is manifested in the entry of electrons and ions in the dayside magnetosphere. In particular, we will use both generic/idealized discontinuities with different field and plasma parameters (e.g. fast rotations of the interplanetary magnetic field (IMF), density enhancements, embedded current sheets, interplanetary shocks) and event studies to investigate how the impact of solar wind discontinuities can affect reconnection processes and the precipitation of low-to high energy particles in the cusps. Simulation results will be used to understand and tabulate characteristic precipitation signatures driven by the impact of different types of solar wind structures. By comparing these signatures with spacecraft observations and correlating them with the state of the magnetosphere observed after the discontinuities have affected the entire magnetosphere will allow us to associate dayside precipitation signatures with the geoeffective responses to different types of solar wind structures.

The methodology of the research will be based on carrying out a series of large-scale iPic3D simulations that will use global MHD simulations to determine their initial and evolving boundary conditions. While the investigation will be based on actual events using observations from the MMS, Cluster, THEMIS, and DMSP spacecraft, a key element of the study will be to first use a series of idealized forms of the solar wind input that include the fundamental characteristics of the discontinuities of interest. This approach will allow us to grasp the primary physical processes involved before using actual solar wind measurements to obtain quantitative assessments of the simulation results by comparing them to observations. In particular, case studies for intervals when the spacecraft provide suitable conjunctions in the ionosphere, magnetosphere, and near Earth solar wind will be used to evaluate how uncertainties in the input data and the simulation assumptions affect the results of the model.

The proposal will address directly the science objectives targeted by the Focused Science Topic (FST) # 3 of the ROSES-2018 LWS program (Understanding the Response of Magnetospheric Plasma Populations to Solar Wind Structures). By improving the quantitative assessment of the kinetic effects associated with the impacts of solar wind structures on the dayside magnetopause, our proposed research will advance the development of the next generation of models to forecast the effects of geoeffective disturbances. In addition, the results of the investigation could motivate the discovery of new features occurring as solar wind structures interact with the dayside magnetosphere.

Douglas Braun/NorthWest Research Associates, Inc
Active Region Dynamics and the Variability of Meridional and Zonal Flows

Using helioseismic data analysis and numerical modeling we will assess the properties of flows related to magnetic fields on the Sun, including plage and active regions across a wide range of magnetic flux, and their contribution to the meridional and zonal components of global solar flows. Motivated by the recent discovery of high-latitude flow features, which may indicate convective giant cells, another component of our observing program is to explore in higher resolution the nature of high-latitude flows, their relation (if any) with magnetic fields, and their contribution to global dynamics.

Primary tasks include carrying out a high-resolution holography survey of flows around magnetic regions using HMI observations from the Solar Dynamics Observatory. We will use spatially coaligned ensemble-averages of near-surface calibrated flows, measured using helioseismic holography, to characterize the flows associated with active regions as a function of magnetic flux (from small regions with 10^20 Mx flux, to the largest observed in the current solar cycle), and as the regions evolve with time. A smaller survey of giant-cell candidates will also be performed. We will employ forward and inverse modeling of these averages, designed to maximize the signal-to-noise, to infer the depth variation of these flows. The contribution of these local flows to contemporary global meridional and zonal measurements, such as the torsional oscillations, will be assessed as a function of time for the duration of solar cycle 24. This is facilitated by identifying and accounting for the flows from active regions from daily synchronic magnetograms and employing our catalog of ensemble-averaged flows to perform high signal-to-noise longitudinal averages. The result will enable a separate characterization of the global, time-varying, dynamics and the local active-region flows, both of which are necessary as inputs to flux transport models and as constraints on solar dynamo and interior modeling. Validating the reliability of both surface and deeper inferences of the flows is achieved using synthetic data derived from state-of-the-art numerical MHD simulations of waves in the vicinity of magnetic regions. A portion of these simulations will have sufficient temporal duration to enable the examination of the physics of the flows, which may result from thermal winds under geostrophic conditions.

The identification and characterization of local active-region flows and giant-cells and their contribution to global dynamics, is critical to the goal of Focus Science Topic (FST) #4 in enabling a data-driven model for solar magnetic flux production to enable forecasting of active latitude and longitude regions over times scales of years or more. Specific to this goal is the establishment of a consensus set of observational constraints of surface and interior flows, with the latitudinal and temporal variation of meridional and zonal flows specifically called out. Our effort contributes directly to three of the suggested investigation types of FST #4, including "observational studies of the spatial structure of internal and surface solar flows," "inversion techniques," and "theory and modeling of large-scale flows."

Manbharat Dhadly/US Naval Research Laboratory
Exploring the high-latitude origin, evolution, and low-latitude impacts of large scale traveling ionosphere/thermosphere disturbances-NRL1

Science Objectives:
Understanding the formation, progression, and global impact of Large Scale Traveling Atmospheric/Ionospheric Disturbances (LSTADs/LSTIDs) is a long-standing challenge in global space weather research. This has been a particularly perplexing problem due to the strongly coupled nature of the high-latitude ionosphere-thermosphere (I-T) system, where they are believed to originate. At high latitudes, the magnetosphere dumps a large amount of energy (both directly and indirectly) into the I-T system through Joule heating, auroral particle heating, and ion drag. LSTADs are a commonly observed thermospheric response to magnetospheric energy entering the I-T system. It is believed that LSTADs

drive a similar wave response in the ionosphere, known as LSTIDs. Recent studies suggest that LSTADs/LSTIDs may also play an important role in transporting high-latitude variability to lower latitudes.

Our knowledge of the origin, evolution and impact of LSTADs and LSTIDs is still very limited. This is due to the scarcity of the data and the inability of the models to accurately capture LSTIDs and LSTADs. New models have shown significant improvement in capturing the complexity of the full I-T system and increasing networks of observational instrumentation now provide sufficient geographic coverage to trace the propagation of LSTIDs and LSTADs. With these updated tools, it is finally possible to address the following focused science questions:

1. How do auroral disturbances generated by magnetospheric forcing drive LSTADs/LSTIDs?
2. Do the background conditions control LSTAD/LSTID generation and propagation to lower latitudes?
3. What is the effect of LSTADs/LSTIDs on the low-latitude longitudinal variations of the I-T system, and how does this affect the longitudinal distribution of the total electron content (TEC)?

Theoretical calculations and observations have indicated that LSTADs are launched from the auroral regions due to: (1) perturbations in the auroral electrojet current, (2) thermospheric heating caused by highly energetic particles from the magnetosphere, and (3) rapid motions of the aurora. Since both LSTIDs and LSTADs can propagate longitudinally and latitudinally on a global scale, they can transport energy and dynamics from high to middle and equatorial latitudes, impacting their thermosphere and ionosphere weather. It is not known under what conditions they are able to effectively transport energy to low latitudes or how that energy transport affects the longitudinal distribution of the ionospheric density. Answers to these questions are essential if we are to bridge the gaps in our current understanding of LSTADs, LSTIDs, and their impacts on the structure of the lower and equatorial latitude regions.

Proposed Contribution to FST:
The proposed effort directly addresses the first Focused Science Topic: Mid-latitude and Equatorial Dynamics of the Ionosphere-Thermosphere System. The goal of the FST is to understand the mid to low latitude plasma density distribution, which is believed to be affected by the propagation of LSTADs/LSTIDs from high latitudes. The proposed work is to specify and quantify how LSTADs/LSTIDs are generated and how they transport energy from high to low latitudes, affecting the longitudinal structure of TEC.

Methodology:
We will utilize two-way coupled WACCM-X (Whole Atmosphere Community Climate Model, Extended) with the three-dimensional first-principles model SAMI3 to simulate LSTADs and LSTIDs and then validate the results against available observations (TEC, NASA C/NOFS, ISRs, GOCE, and CHAMP). The coupled model will use the Weimer model for high-latitude potential and the Hardy model for auroral particle precipitation to

provide high-latitude drivers. The system will be run with varying model components to isolate physical processes responsible for particular phenomenology and compared with observational data to achieve closure on the science questions.

Mausumi Dikpati/University Corporation For Atmospheric Research (UCAR)
Simulating active longitudes by coupling magnetograms with a nonlinear MHD tachocline model: a data assimilation approach

This project addresses the Focused Science Topic (FST) #4: Understanding Global-scale Solar Processes and their Implications for the Solar Interior, which addresses LWS program objective 1: Understand how the Sun varies and what drives solar variability.

Scientific goals and objectives: The goal of this project is to simulate the timing, strength and latitude-longitude location of activity bursts, called active longitudes, and their subsequent evolution, which play a crucial role in creating the major space weather events that impact the Earth. The objective is to simulate active longitudes up to several months and even 1-2 years in advance. Therefore this project includes prediction as an applied component. As required by NASA for LWS-FSTs, this project will address the uncertainties in the data, model and simulation. Our measure of success will be prediction of the strength, timing and locations of active latitudes and longitudes for the next solar cycle, cycle 25, in addition to hindcasting cycles 23 and 24.

Methodology: The method builds on our recently developed global, nonlinear, MHD 'shallow water' model of the solar tachocline. This model has already demonstrated the existence of Tachocline Nonlinear Oscillations (TNOs) that produce the seasonal (6-18 months) solar variability and potentially can be the source of amplitude, latitude and longitude variations of the bursts of activity. Our model will dynamically evolve the dynamo-generated toroidal fields that are already present in the tachocline, along with the differential rotation, MHD Rossby waves and bulges of the tachocline upward into the convection zone. The bulges that contain dynamo-generated sunspot-producing toroidal fields will be the sources for imprints of emerging magnetic flux that are then compared with magnetic patterns observed at the surface. We will use a physical model to relate the bulging toroidal fields to emerged flux at the surface. We will couple a data assimilation capability to the MHD tachocline model, into which we will assimilate surface magnetic data from SDO/HMI, to advance the model-outputs, to simulate and predict the amplitude, surface location and eruption timing of emerged magnetic patterns, i.e. active longitudes. This predictive tool will be validated through hindcasts of active longitudes during solar cycles 23 and 24. We will also apply information theory to observational and simulation data, for example, to examine the information flow and response timing between the bulging toroidal field and emerging magnetic flux at the surface. We will use the same technique to explore the links of the activity bursts with other ingredients, including Rossby waves and differential rotation.

Contributions to the Focused Science Team effort: This study mines global MHD simulations of the solar tachocline and its connection to surface magnetic observations, in order to assist interpretations of other global studies of the solar interior, including variations in differential rotation and meridional circulation and helioseismic inversions. Our model includes tachocline MHD for all latitudes, so it is ideal for complementary understanding of new observations and inversions of high latitude phenomena. Our model will also be complementary to solar dynamo models, which are simulating solar cycles and spot-producing magnetic fields, but have not yet simulated active longitudes. Our model, coupled with data assimilation technology, will dynamically evolve the dynamo-generated fields to simulate and predict active longitudes. The coupled model-system will create predictive tools, including the potential for real-time updating, which is particularly encouraged by NASA for this FST. Furthermore, our information theory-based technique can easily be applied to data produced by other team members under this FST.

John Dombeck/University Of Minnesota
Characterization of M-I coupling electron populations and ionospheric altitude dependence on solar wind conditions and structures

Magnetospheric-ionospheric (M-I) coupling plasma populations are some of the most important in the magnetosphere. They are a primary means through which solar wind (SW) energy and dynamics are transmitted to the ionosphere-thermosphere-mesosphere (ITM). They are also the primary means through which the ITM feeds back to the magnetosphere and are often the source population for higher energy magnetospheric particle populations. Having an accurate understanding of these populations, the M-I interface, and how these populations depend on SW drivers and structures and on ionospheric conditions is critical to understanding the effects that SW structures have on the magnetosphere.

We propose to develop and provide an empirical model for the dependence and range of variability of M-I coupling electrons, including precipitating, ionospheric, and mirroring populations, with unprecedented detail (including energy spectra) based on SW and geomagnetic conditions. Additionally, utilizing the same data, an empirical model for ionospheric scale height and heights at which various energy electrons deposit their energy will be developed. Finally, the database used to create the models will also be used to determine the effects specific SW structures have on these populations and ionospheric height characteristics.

The main science goals and objectives of our proposed effort are to:
1) fully characterize the electrons involved in M-I coupling in the ~5-30,000 eV range and develop an empirical model for their dependence on SW and geomagnetic conditions;
2) characterize the ionospheric scale height in auroral latitudes and develop an empirical model for their dependence on SW and geomagnetic conditions;

3) determine how specific solar wind structures affect the M-I coupling electron populations and ionospheric scale height.

The proposed study will utilize the full, nearly 13-year, mission data from the FAST satellite to develop a database of full pitch angle distribution electron data over the pertinent energy range and SW, geomagnetic and footpoint/conjugate footpoint illumination conditions. This database will be used to develop an empirical model for the expected and range of spectra for precipitating, mirroring and ionospheric electrons based on SW and other conditions. A separate empirical model of ionospheric height characteristics will also be developed from the same database by examining the variations in partial mirroring near the loss cone boundary angles. Finally, FAST passes during case studies of SW structures (shocks, CME, etc) interacting with the magnetosphere will be examined and compared to the empirical model output to determine the effects these structures have on the M-I coupling electron populations (and ionospheric height characteristics).

This proposed effort is directly relevant to and will directly and indirectly contribute to the FST. In particular, it will develop a highly improved empirical model for very important magnetospheric plasma populations as a function of SW and geomagnetic conditions. It will also examine case studies utilizing both the empirical models and actual data. The resulting database and empirical models will also be useful to the FST for validating and providing inputs for other models of SW-M-ITM coupling and dynamics, even for times and events outside of the FAST mission. Case study analysis of both the empirical model results and similar events in the FAST database for events selected by other members of the FST are also part of the scope of the proposed effort, and the models will be made generally available to the community. Comparison to the compiled database will also provide a means evaluating intrinsic errors for extreme events both in our models and those of other FST members. Metrics and milestones of success will include completing the database, implementation of the empirical models, individual case studies and comparison of model output to individual FAST pass data.

Nicholas Featherstone/University Of Colorado, Boulder
Processes Shaping the Solar Meridional Circulation

Overview:
The Sun's deep-seated convective flows must ultimately sustain both the efficient EMF from which solar magnetism derives and the differential rotation and meridional circulation thought to imbue that magnetism with its remarkable spatiotemporal ordering. Exploration of the dynamo process ultimately requires knowledge of how these deep convective flows are structured, and yet present helioseismic techniques have only recently been able to image flows in the lower portion of the convection zone. Therefore, our understanding of the deep interior has been heavily predicated on numerical models. Such models have identified the structure and speed of the meridional circulation cells as crucial ingredients. Through the use of 3-D, nonlinear convection simulations, we

propose to explore those dynamical processes that shape the solar meridional circulation, thus providing overlap between deep convection models and helioseismic observations.

Science Goals and Objectives:
The role that convective-flow speed plays in determining the morphology of solar meridional circulation is now well established, but the effects of boundary layers and magnetism on the circulation speed and morphology have yet to be systematically examined. Our science goals, which follow, center around exploration of these two effects.
1. We will examine how the convection zone's boundary layers impact the properties of meridional circulation, particularly the multi- or mono-cellular nature of the flow.
2. We will explore how Lorentz forces associated with deep-seated dynamo action impact the shape and speed of meridional circulation. We will assess what the form of meridional circulation implies about the underlying dynamo mechanisms at work.
3. Through direct comparisons with ongoing observations and modeling efforts from the broader FST science team, we will use our models of meridional circulation to place constraints on the mode of dynamo operating in the deep convection zone.

Methodology:
We will construct a suite of global, numerical convection simulations that encompass the bulk of the convection zone. Through these simulations, we will examine how magnetism and overshooting impact the structure of deep meridional circulation. In tandem with observations, these models will be used to constrain the structure of solar convection and mean flows throughout the convection zone.

Spherical simulations will be conducted using the Rayleigh convection code. Rayleigh is open-source software that solves the MHD equations of motion for a compressible fluid in a rotating spherical shell under the anelastic approximation. It has been performance tested extensively on NASA's SGI Pleiades system and Argonne's Blue Gene/Q system, Mira. Rayleigh exhibits efficient parallel scaling on up to 524,288 Mira cores for problems of size 2048^3 grid-collocation points.

Proposed Contributions to FST Effort:
Our team will provide a theoretical, dynamics-oriented component to the FST. Results arising from the pursuit of our scientific objectives will have synergy with multiple sub-teams of the FST. In particular, we envision that our first-principles models will provide a bridge between helioseismic observations and reduced models of the solar dynamo. Our data products will be used to test helioseismic techniques and to train and inform dynamo models that are capable of providing detailed predictions of magnetic field evolution in the photosphere and corona.

Relevance to NASA Objectives:
This work addresses the first and fourth challenges identified in the 2013--2022 Decadal Survey in Solar and Space Physics: "Determine the origins of the Sun's activity and predict the variations of the space environment," and "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the

universe." These questions frame the science objectives of many NASA missions, most notably the Solar Dynamics Observatory (SDO).

Xiangrong Fu/New Mexico Consortium
Heating of Ions in the Low-beta Compressible Solar Wind

The solar wind is the high speed plasma flow originated from the Sun, carrying magnetic field and energetic particles and propagating throughout the heliosphere. In-situ measurements have shown that solar wind is turbulent and ions are heated, though the heating mechanisms for solar wind ions are still under debate and a subject of active research.

We propose to study the solar wind ion heating in the regime when the turbulent Mach number is high (between 0.1 and 1) and the plasma beta is low (< 0.1), i.e. the low-beta compressible turbulence (LBCT) regime. This regime is particularly relevant in the near-Sun region where the solar wind originates and the magnetic energy density is large, though such conditions can exist throughout the heliosphere. In particular, we will study the critical role of the parametric decay instability (PDI), which converts a large-amplitude forward Alfven wave into a backward Alfven wave and a slow mode. The backward Alfven waves can further interact with forward Alfven waves and produce a plasma turbulence mixed with compressible and incompressible components. Our recent MHD and kinetic simulations show that, in this regime minor ion species undergo efficient heating, with distinctive signatures in both parallel and perpendicular directions. Specifically, we will address three key science questions (SQ):

1) Can PDI explain enhanced density fluctuations at the center of the preferential ion heating zone (10-20 solar radii)?

2) What are the heating rates of compressible and incompressible turbulences on protons and minor ions in the low-beta compressible solar wind?

3) How does the inclusion of ion heating from compressible turbulence improve global modeling of the solar wind?

Because LBCT have been observed in the heliosphere from tens of solar radii to a few AUs, with an increasing occurrence when approaching the Sun, our proposed investigation is very timely to address the long-standing ion heating problem in the solar wind because in-situ measurements in the close-to-Sun region will soon be made available by the Parker Solar Probe (PSP).

We propose to perform local 3D MHD and hybrid simulations to address the problem of solar wind ion heating in the low-beta compressible regime, using turbulence and plasma quantities provided by global MHD simulations. The local MHD simulations will enable us to examine the similarities and differences of properties between compressible turbulence and the well-studied nearly incompressible turbulence. Hybrid simulations will allow us to directly examine the detailed ion heating processes in the low-beta compressible regime. Specifically, we will use the background plasma conditions including magnetic field, plasma density, ion temperature and the solar wind speed in several typical regions: 1 AU, 0.3 AU and 10s R_s (solar radius) and <2R_s, from observations and global MHD simulations. We anticipate to carry out a large set of hybrid simulations to study PDI and its contribution to density fluctuations. With kinetic ions properly modeled, their heating rates by compressible waves and turbulence can be quantified, and empirical models of heat functions will be derived. These studies will enable us to test competing solar wind heating mechanisms which could have different ion heating signatures and provide critical microphysics inputs for the global solar wind evolution models.

Natalia Ganushkina/University Of Michigan, Ann Arbor
Response of magnetospheric keV electron population to solar wind structures

1-200 keV electrons are one of the primary constituents of the radiation environment which pose a serious risk for satellites due to surface charging. The keV electron fluxes vary on the scale of minutes or shorter, being extremely sensitive to current solar wind driving. We propose to investigate what specific features in the solar wind structures (ICMEs, shocks/sheaths, CIRs, high speed streams, and their combinations) drive the variability of the magnetospheric keV electron population. We will start with the analysis of solar wind and interplanetary magnetic field structures themselves, and then study in details their influence on the variability of keV electrons. The computational view on the responses of keV electron radiation to solar wind structures is now feasible, since necessary data and the Inner Magnetosphere Particle Transport and Acceleration model (IMPTAM) are available.
Science goals and objectives: The proposed research is targeted to specify the variability of the keV electron radiation environment at 2-10 RE in response to the solar wind structures impinging on Earth s magnetosphere with specific focus on variations along GEO and MEO. Three questions will be answered: (1) What are the main effects from the spatial-temporal details of the solar wind structures (ICMEs, shocks/sheaths, CIRs/SIRs, high speed streams, and their combinations) on the transport and acceleration of keV electrons reaching GEO? (2) Are the driving by different solar wind structures and associated transport and acceleration of keV electrons different inside GEO and at MEO? (3) Sources, losses and substorms: What is the most important factor (or combination of factors) for keV electrons dynamics? By answering the science questions, we will understand the keV electrons variability and will significantly increase our predictive abilities.
Methodology: Using Wind and ACE proton kinetic properties as well as ion composition data combined with magnetic field measurements, we will analyze the spatial and temporal details of the structures of interplanetary features impinging on Earth s magnetosphere. Specific solar wind parameters from different solar wind structures will be used for driving IMPTAM for keV electron simulations (< 200 keV). The processes of

the formation of keV electron population will be studied and, in particular, we will examine the role of substorms in it. IMPTAM will be validated on the large data sets from GOES and Van Allen Probes. Rigorous uncertainty estimates are an essential part of the project, which will be quantified using the NARMAX model.
Proposed Contributions to the Focused Science Team Effort: The proposal attacks one of the fundamental questions for inner magnetosphere physics and will provide a critical link in our community's ability to understand radiation belt dynamics. The proposal largely contributes to the Objective 2 of the LWS program, Understand how the Earth & respond to dynamic external and internal drivers , by providing the scientific understanding of the keV electron dynamics and the ability to predict it, as a part of the bigger picture of the Heliosphere as a system. The project directly addresses one of the Focused Science Topics (FST), namely, 3) Understanding the Response of Magnetospheric Plasma Populations to Solar Wind Structures. The results of the proposed investigations have the direct relevance to the scientific objectives FST 3 as the improved and validated first principle model IMPTAM capable of predicting the time-dependent response of keV electron population to varying solar wind conditions. Several milestones set for the duration of the proposed project will ensure the successful progress of the research. Validated IMPTAM output in the entire inner magnetosphere and the set of metrics developed for IMPTAM performance will be the important contribution to the FST Effort.

Michael Hahn/Columbia University
Observational Constraints on the Origin and Acceleration of Solar Wind from Coronal Holes

Science Goals and Objectives:

Understanding the solar wind requires determining the source regions for different types of solar wind and the physical processes that accelerate them. We propose to investigate the solar wind from within and near coronal holes (CHs). These open field regions are the source of fast solar wind. Their boundaries are thought to be a source slow solar wind. Theories propose that at CH boundaries reconnection occurs between open and closed magnetic field, releasing stored plasma onto open field lines to form the slow solar wind. Many characteristics of this interchange reconnection process are unknown.

We propose to use elemental abundances as a diagnostic to understand interchange reconnection. The abundances of elements with a low first ionization potential (FIP) grow over time on closed loops. This FIP effect does not occur on open field lines. Thus, the FIP effect can be used to determine how recently a closed field line has undergone reconnection with an open field line. We will study the FIP-effect at the boundaries of CHs and use our results to infer the length and time scales over which interchange reconnection occurs at the CH boundary.

Reconnection is driven by random convective motions and by large scale flows, such as differential rotation. CHs are known to not be sheared by differential rotation of the photosphere. Theories suggest that this is because reconnection at the boundary maintains the CH's shape. We will study differences in the FIP effect gradients on the leading and trailing edges of CHs to determine whether they are consistent with this theory for CH rigid rotation.

A well-known empirical property of the solar wind is the inverse correlation between the wind speed and the expansion factor describing the divergence of magnetic field lines in the low corona. It has been argued that the expansion factor is just a proxy for the solar wind source distance from the coronal hole boundary (DCHB). These different correlations are related to different physics as the expansion factor is important for wave-turbulence driven solar wind models, whereas the DCHB is important for reconnection-driven models.

We will measure the solar-wind outflow velocity at low heights in the corona and determine the correlation between velocity, expansion factor, and DCHB. This will show whether the correlation observed in the solar wind is present at low heights and whether expansion factor/wave-driven models or DCHB/turbulence-driven models are more important.

Methodology:

We will use spectroscopic data from EIS on Hinode, as well as magnetograms and images from SOHO and SDO, to study low latitude CHs. Many suitable public archival datasets already exist. From the EIS data, we will derive the elemental abundances and Doppler velocities and produce maps of these quantities throughout the field of view. We will determine how the FIP effect varies across the CH boundary. We will also study how the abundances vary as a function of latitude at the leading versus trailing edges of the CH in order to observe the effects of differential rotation.

From the magnetograms we will extrapolate the coronal magnetic field using magnetic field models. Potential field models are expected to be sufficiently accurate, but we will use other models to quantify systematic uncertainties. These results will allow us to de-project the line-of-sight velocities to measure the flow velocity along the field. From the model, we will also obtain the expansion factors and find the correlation of flow velocity.

Imaging data will be used to specify the boundary of the CH. In reality, the boundary is gradual and so different conventions and algorithms have been proposed in order to specify a particular location. We will use different conventions in order to quantify systematic uncertainties. Then we will find the correlation between flow velocity and DCHB.

Chaosong Huang/Air Force Research Laboratory
Dynamic and Coupling Processes in the Mid-Latitude and Equatorial Thermosphere and Ionosphere during Geomagnetic Storms

A compelling challenge in the study of global ionospheric electrodynamics during geomagnetic storms is to identify and characterize penetration and disturbance dynamo electric fields and their impacts on the behavior of the ionosphere during geomagnetic storms. The objective of this proposed work is to achieve breakthroughs in understanding and quantifying storm-time penetration and dynamo electric fields in the mid-latitude and equatorial ionosphere through comprehensive data analysis and physics-based model simulations. Ionospheric electric fields play a key role in the Sun-Earth connection as they are the result of direct coupling between the solar wind and the magnetosphere/ionosphere system and between thermospheric neutrals and ionospheric plasma. However, many aspects of the fundamentals of storm-time penetration and dynamo electric fields are still not well understood. Recent studies have revealed that penetration electric fields play a much more important role in ionospheric storms than previously thought and that disturbance dynamo electric fields can dominate equatorial electrodynamics for a long period of time (e.g., 20 hours) after a magnetic storm ceases.

We propose to undertake a comprehensive study of the storm-time behavior of mid-latitude and equatorial ionospheric electrodynamics and its interaction with the thermosphere using analysis of data from global observations and state-of-the-art first principles modeling. The specific goals of this effort are to address the following outstanding science issues:

(1) What are the Characteristics of Penetration Electric Fields in the Equatorial Ionosphere during Geomagnetic Storms?

(2) What are the Characteristics of Disturbance Dynamo Electric Fields in the Equatorial Ionosphere during Geomagnetic Storms?

(3) How Long Does Shielding Electric Field Take to Grow to Its Maximum Level? Can Shielding Electric Field Be Strong Enough to Cancel Penetration Electric Field?

(4) What are the Longitudinal Variations of Ionospheric Electric Fields during Geomagnetic Storms?

We will analyze extensive data sets from multiple satellites and ground-based measurements and run the physics-based LTR model, which couples the Lyon-Fedder-Mobarry (LFM) Magnetospheric MHD Model, Rice Convection Model (RCM) of the inner magnetosphere and ring current and the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) through the Magnetosphere Ionosphere Coupling/Solver (MIX), to address the above science issues. Data from the Defense Meteorological Satellite Program (DMSP), Communication/Navigation Outage Forecasting System (C/NOFS), Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED), and other satellites, as well as ground based measurements, will be used to investigate the characteristics and changes of ionospheric electric fields during geomagnetic storms. The LTR model, driven by the observed solar wind data, will be run for different types of geomagnetic storms to compare with data. The four science issues will be addressed through data analysis, model simulations and comparison between model outputs and observations. The combination of expertise of the team members in modeling, observations, and data analysis assures the success of the proposed work.

The proposed work is directly related to 2018 LWS Focused Science Topic #1 Mid-latitude and Equatorial Dynamics of the Ionosphere-Thermosphere System . The proposed work will contribute to the LWS program objective by providing a quantitative specification of the ionospheric electric fields during geomagnetic storms and a comprehensive understanding of the variations of the electric fields. The expected results of this project will advance our understanding and knowledge of ionospheric dynamics and provide fundamentals for developing the forecasting capability of storm-time ionospheric behavior.

Lan Jian/NASA Goddard Space Flight Center
Investigating the Interaction between Solar Wind Ions and Electromagnetic Waves Using New Observations and Hybrid Simulations

Electromagnetic cyclotron waves (ECWs) are extensively observed in the solar wind from 0.3 to 1 AU. They appear to be left-hand or right-hand polarized in the spacecraft frame, and propagate in directions close to the background magnetic field. On the other hand, the solar wind is often not in equilibrium, featured with the temperature anisotropy of particles with respect to the background magnetic field and relative drifts among ion components (proton core, proton beam, and alpha particles). The ECWs near the proton cyclotron frequency are most likely to have Landau and/or cyclotron resonances with solar wind ions. Using well-calibrated magnetic field and plasma data from Wind (continuous solar wind monitoring) and MMS mission (providing about 3 hours of high-cadence solar wind data per 3-day orbit), we will investigate the interaction between ECWs and solar wind ions.

Since the ion kinetic scale marks the transition from the inertial range to the dissipation range, our investigation directly addresses the acceleration and evolution of solar wind, which is the second Focused Science Topic of this LWS solicitation. In particular, we aim to answer the following three science questions. (1) How often are non-equilibrium ion velocity distributions and ECWs observed together in the solar wind? (2) In the case of multiple unstable modes of ion kinetic instabilities, how do the different modes interact? (3) Do all the instabilities propagate along with the solar wind?

In the solar wind, three types of ion-driven instabilities can generate such parallel-propagating ECWs: ion cyclotron, parallel firehose, and ion beam instabilities. There is often multiple sources of free energy for waves to grow. To fully investigate the nonlinear interaction between the different instabilities, we will conduct the hybrid simulation guided by solar wind observations. Our methodology includes the following three aspects. (1) We identify ECWs using Wind data and compare their existence with the growth rates of multiple ion kinetic instabilities to explain the discrepancies of their occurrence rates. (2) We search 20 long-lasting ECW events of multiple coexistent unstable instabilities using 2005-2007 Wind data, and examine how the different modes interact using hybrid simulation. (3) We search ECWs (especially the cases of close appearance of opposite polarizations) in the solar wind using MMS data and determine the wavevector and intrinsic polarization. By conducting hybrid simulations for selected events, we determine whether the unstable instabilities propagate along or against the solar wind.

The coherent electromagnetic waveforms and detailed particle velocity distributions provide unique opportunities to study the wave-particle interaction at ion kinetic scales. The improved understanding of ion kinetic physics through this coordinated project will be applicable to plasma in planetary magnetospheres and ionospheres, astrophysical systems, and laboratory plasma experiments. As more solar wind models and CME models start to incorporate the kinetic effects, the better understanding of wave-particle interaction gained from this project will ultimately help improving the prediction of solar wind and CME properties.

Rudolf Komm/Association Of Universities For Research In Astronomy, Inc.
Do Flows in the Upper Solar Convection Zone Drive Global-Scale Magnetic Fields?

Science goal and objectives: We propose to measure the flows from the surface down to the upper shear layer in the convection zone around 5% below the surface and provide observational constraints for the latitudinal, longitudinal, and temporal variations of the flow components. The goal is to establish the extent to which these large-scale flows drive the emergence and evolution of magnetic flux at the solar surface and the subsequent poleward flux transport. This will lead to a better understanding of the generation and evolution of global-scale magnetic fields.

To achieve this goal, we will focus on surface and subsurface large-scale flows near locations of activity, including activity complexes and active longitudes, and search for subsurface markers or even precursors of magnetic activity. Second, we will focus on flows at mid- to high latitudes where diffusing flux is being transported poleward. Third, we will focus on the solar-cycle variation of flows derived from locations of high or low activity and the North-South asymmetry in magnetic activity and its connection to subsurface flows and whether these flows are precursors of the next-cycle activity. We will study the flows in three depth ranges: the layers close to the surface, where the density changes by several orders of magnitude, the near-surface shear layer (NSSL, at about 35 Mm), where the rotation rate shows a local maximum, and the layers in between these two. The flows in these layers have the most direct influence on surface activity.

Methodology: We will perform a comprehensive study of the large-scale horizontal flows (zonal and meridional flows) from the surface to a depth of about 40 Mm (94% solar radius) from the equator to 70 degree latitude or higher. We will focus on their variation with latitude, longitude, and time. We will study the variation from one rotation to the next and during the course of a solar cycle.

To derive the subsurface flow components, we will apply ring-diagram analysis (a well-established helioseismic technique) to SDO/HMI Dopplergrams. As a starting point, we will use the flow values derived from the standard HMI ring-diagram pipeline with three different tile sizes. We have previously studied the subsurface flows in the near-surface layers (to a depth of 16 Mm) with velocities from the HMI 15-degree ring-diagram pipeline. For the proposed study, we will, in addition, use tiles as small as 5 degrees for a better spatial and temporal resolution near the surface and big tiles of 30 degree to cover the NSSL. We will then customize the ring-diagram analysis modifying the grid size as well as the grid spacing and the tracking rate to optimize the analysis for the proposed project. We will derive the systematic variations of the flows with disk position and correct them.

To derive the flows near the NSSL, we will also apply helioseismic time-distance analysis to SDO/HMI Dopplergrams. Since time-distance and ring-diagram analyses have different error characteristics, this will allow us to cross-validate the results from both techniques.

To derive flows at the solar surface, we will use f-modes derived from SDO/HMI Dopplergrams and an appropriate LCT technique applied to SDO/HMI Dopplergrams and vector magnetograms. This will allow us to compare three sets of surface flows from different techniques and data sets.

Proposed Contributions to the Focus Team Effort: The proposed study of the large-scale flows in the upper convection zone will provide observational constraints, which will be crucial for the modeling of the solar interior and the solar flux transport. This will lead to a better understanding of the generation and evolution of global-scale magnetic fields and, as a consequence, provide constraints for forecasting solar activity. The proposed study therefore addresses the objective of Focused Science Topic (4): Understanding Global-scale Solar Processes and their Implications for the Solar Interior.

Enrico Landi/University Of Michigan, Ann Arbor
Understanding solar wind acceleration from global models, remote sensing and in-situ observations

Science goals and objectives
In the present investigation we will study solar wind heating and acceleration through Alfven waves by combining existing in-situ measurements obtained with the SWICS instrument on board the ACE and Ulysses spacecraft, high resolution spectra and narrow band images of the solar atmosphere with Hinode, SDO and SoHO, and the 3D MHD AWSoM model of the solar corona and the solar wind. This work will encompass cycles 23 and 24 through the use of multiple in-situ and remote sensing instruments, and can be extended, capitalizing on the results obtained with existing observations, to data from the Parker Solar Probe and the upcoming Solar Orbiter mission.

Methodology
This methodology will combine the AWSoM model predictions of the 3D distribution of plasma speed, temperature and density with 1) the SPECTRUM module, which calculates line-of-sight images and high resolution spectra of the solar corona from any user-defined line of sight, and 2) the Michigan Ionization Code (MIC), which allows to calculate the evolution of the charge state distribution of the wind plasma with distance. Individual wind source regions, such as polar and equatorial coronal holes, streamers, active regions, will be connected to ACE and Ulysses positions through AWSoM magnetic field calculations; comparison of AWSoM/MIC/SPECTRUM predictions of spectra, images and plasma properties of the wind source regions with remote sensing observations and measurements, and AWSoM/MIC predictions of wind charge state distribution with the measurements magnetically connected to the wind source at the Sun, will allow us to 1) assess AWSoM s ability at predicting plasma heating and acceleration, 2) carry out empirical modeling of the wind evolution, to determine the plasma temperature, density and speed before the freeze-in point, to be compared with AWSoM predictions, and 3) characterize Alfven wave properties through comparison of predicted and observed line widths.

Proposed contributions to the focus science team effort
Relevance to FST Scientific objectives: This combination of observation and modeling provides unique contributions to the FST: it will allow the determination of which observables (individual spectral line intensities and profiles, charge states etc) are critical towards understanding the effects of Alfven waves on heating and acceleration; it will allow us to determine how the solar wind charge state composition is set; it will provide vital input towards improving the AWSoM model, enhancing its space weather and solar wind predictive capabilities; it will allow us to understand how the effects of observational and modeling uncertainties on wind diagnostics can be mitigated.
Potential contributions to FST effort: This investigation combines observations and numerical modeling to directly address several Types of Investigations such as: minor ions and their role in the origin and the evolution of the solar wind, solar wind source models based on charge state and elemental composition, evolution of solar wind properties through the solar cycle.

Metrics and milestones to success: During the first year, remote sensing and in-situ observations will be used to identify the best diagnostics of wind heating and acceleration. In year 2, high resolution spectra and charge states will be used to determine, together with the diagnostic techniques identified during year 1, , the ability of AWSoM to match measurements for a few select Carrington Rotations across the solar cycle. Years 3 and 4 will apply these diagnostics on predictions from the fine-tuned model, and investigate the evolution of the source regions, the Alfven wave properties, and the plasma properties in the solar atmosphere during cycles 23 and 24.

Jinxing Li/University of California, Los Angeles
Ring current dynamics and associated wave activity in response to solar wind drivers using machine learning

science objectives:
This project aims to model and predict the dynamic evolution of ring current ions and the associated waves in response to different solar wind drivers using machine learning technique and wave-particle interaction simulations. The ring current enhancement is the direct cause of geomagnetic storms, which impact telecommunication and navigation systems, as well as power grids. The electromagnetic ion cyclotron (EMIC) waves and magnetosonic waves that grow from ring current ion instabilities can scatter the ring current ions and radiation belt electrons via wave-particle interactions. Therefore, quantitative understanding of the ring current dynamics is crucial in predicting global space weather and protecting spacecraft. The science goals of this project include:
1. Establishing a 3-D ring current ion energy distribution and pitch angle distribution model at different radial distances, magnetic latitude and local times in response to the solar wind drivers using machine learning technique.
2. Predicting the wave distribution due to ring current ions instabilities, including the EMIC waves and magnetosonic waves, and their response to solar wind drivers and geomagnetic indices.
3. Calculating the decay rates of ring current ions from the machine learned ring current model. Evaluating the ion loss caused by scattering from EMIC waves and magnetosonic waves.
4. Investigating the nonlinear ion scattering and acceleration caused by waves using test particle simulations.

Methodology:
1. We will utilize multi-point measurements to study the ring current dynamics and the associated wave activities from a global view. The data to be used includes ion fluxes, magnetic field, and wave spectra from 2 Van Allen Probes, 3 THEMIS satellites, and the Arase satellite.
2. We will use the machine learning technique to model the ion dynamics in response to different geomagnetic indices (Dst index, AE index, etc.) and solar wind drivers (IMF dynamic pressure, magnetic field, etc.).
3. We will use the quasi-linear diffusion simulations to model the ions loss rate caused by scattering from EMIC waves and magnetosonic waves.
4. We will use test particle simulations to study the linear/nonlinear interactions between ring current ions and waves.

Proposed Contributions to the Focused Science Team Effort:
Our proposed project directly targets Goal #3 of the FST, understanding the response of magnetospheric plasma populations to solar wind structures . By modeling the ring current dynamics using the machine learning technique and utilizing multi-spacecraft observations, we will target the goal of improving empirical models for the magnetospheric plasma environment as a function of solar wind and geomagnetic conditions . By modeling the wave growth from the ion instabilities, and simulating the

linear and nonlinear scattering of ions and electrons caused by those waves, we will target the goal of improving our understanding of nonlinear response to different driving conditions, involving coupling and feedback between populations& wave particle interactions , and how particular structures in the solar wind affect global fields and particle populations from a whole systems approach .

Roberto Lionello/Predictive Science Incorporated
The Spatial, Temporal, and Charge-State Variability of the Solar Wind

The solar wind expands outward from the solar corona and fills the heliosphere. It is the medium by which solar-driven space weather phenomena transmit their effects to Earth and the surrounding space environment. Fundamental questions remain about the wind's origin and acceleration, its connection to smaller-scale dynamical phenomena close to the Sun, and the partitioning of the wind into fast and slow streams. Specific examples include:

1) Are topological changes to the magnetic field (e.g. interchange reconnection) in the corona essential for explaining heliospheric solar wind properties?
2) Are density fluctuations related to such processes, and if so, what determines their observed time period?
3) What coronal processes are required to explain ionization charge states in the heliosphere?

To address these questions, we propose to use a magnetohydrodynamic (MHD) model of the solar corona and heliosphere developed at PSI to model specific time periods. The model incorporates the time-dependent evolution of the magnetic field in response to photospheric motions, a wave-turbulence-driven (WTD) description of corona heating, Alfvén wave acceleration of the solar wind, and modeling of ionization charge states. It will be supplemented with comprehensive topological analysis of the magnetic field that identifies different types of magnetic reconnection. Specifically, we will:

* Model the solar wind, in conjunction with the charge states, as it evolves in response to the magnetic field evolution on the solar surface, and compare our results with remote observations and in-situ measurements.
* Utilize an advanced technique for identifying topological changes (i.e., interchange reconnection) in the magnetic field and unravel their role in producing plasma properties.
* Determine whether density fluctuations are also a consequence of the topological evolution of the Sun s magnetic field.
* Connect in situ measurements of the solar wind with the topology of the coronal magnetic field, and provide our results to the LWS team and the larger scientific community.

Our proposed investigation, which aims at furthering our understanding of the solar wind by connecting topological properties with in-situ measurements, density fluctuations, charge states, and the formation of the wind itself, is relevant to FST #2: Origins, Acceleration and Evolution of the Solar Wind. It contains modern theoretical (topological analysis), numerical modeling (MHD), and observational analysis (charge states) elements. We will quantitatively compare our results with remote observations from NASA missions such as SDO, SOHO, and STEREO, and in situ measurements from ACE, PSP, and STEREO. Our project will provide tools for linking these in situ measurements with the remote observations..

Noe Lugaz/University of New Hampshire, Durham
How are Magnetospheric Field and Plasmas Impacted by Impulsive Changes in Interplanetary Parameters?

Science Goals and Objectives: The solar wind flowing past the terrestrial magnetosphere changes in time, sometimes abruptly. Some of these changes are associated with shocks or field/plasma discontinuities that involve one or more parameters. Even for discontinuities involving single parameters one has to take into account the different background plasma and field conditions they occur in (e.g. a density rise in a plasma with strongly northward B; or a north-south deflection of a strong B in a tenuous plasma). Also, shocks may be isolated or may be driven by CMEs and CIRs, and they may be propagating inside a CME. Although the interplanetary (IP) drivers are of short duration, their effects on magnetospheric plasmas and fields can be spread out in time. The strength of the response clearly depends on the amplitude of the impulsive change. Combinations of simultaneous impulsive changes introduce additional features in the magnetospheric response. For example, velocity deflections at a tangential discontinuity introduce a vortex sheet element and the latter results in tangential stresses being exerted on the magnetopause.
Our overall science objective is to understand the effects elicited on the magnetosheath and magnetosphere by specific discontinuities and shocks, with a focus on solar cycle 24. As such, we aim at understanding the wide spectrum of responses of the magnetosphere and magnetosheath to IP discontinuities. To reach this objective, we focus on three science questions: 1) how do discontinuities and shocks affect the magnetosheath and induce asymmetries in plasma and fields at the magnetopause, thereby altering the interaction of the solar wind with the magnetosphere (for example the reconnection rate at the dayside magnetopause)?, 2) how do discontinuities and shock excite waves, field-line resonances, tail-flapping, that affect the magnetospheric plasma?, and 3) can extreme and rapid changes lead to saturation of the magnetospheric response?
Methodology: Our approach is to focus on a set of IP discontinuities: tangential and rotational discontinuities (TDs/RDs) and shocks. The period we examine is that of solar cycle 24, 2007-2018 (11 years). During these years, there is complete coverage of the IP medium from Wind and ACE, and several probes and ground-based data to monitor the response from magnetosheath to the tail. For convenience, we split our investigation into two periods: I. 2007-2014 and II. 2015-2018. First, we isolate the DDs in each period, using Wind or ACE data. We classify them by their strength, any accompanying parameter changes, the background solar wind, etc. We then use observations from a

chain of spacecraft in the magnetospheric system. By using multi-spacecraft observations, we cover a wide spread of MLTs and radial distance from Earth, ideally so that one can track the effects from the bow shock to the geomagnetic tail. For Period I, we use geospace data from THEMIS + CLUSTER + GEOTAIL + GOES and for Period II, we add data from MMS and RBSP.
We undertake mainly analysis and interpretation of field (B and E) and plasma (protons + electrons) observations from space probes and ground-based assets.
Contributions to the Focused Science Team (FST) Effort: The proposed work is directly relevant to the FST as it explores how the magnetospheric plasma and fields respond to various IP drivers. By the end of the investigation, we shall have produced a detailed view of the myriad ways in which the magnetosphere reacts to impulsive changes and any detrimental effects this may occasion in our technology-based society. As a team combining expertise in the study of IP and magnetospheric phenomena, the PI and Co-I will provide their expertise to the entire FST to better understand the complex coupling between the IP and magnetospheric plasma population.

Qianli Ma/Boston University
Quantifying Wave-Induced Relativistic Electron Flux Variations in Earth's Radiation Belts Driven by Solar Wind Structures

Science Goals and Objectives
The relativistic electron fluxes in Earth s radiation belts are subject to various source and loss processes which are ultimately controlled by solar wind structures. The solar wind activities drive global variations of the magnetosphere and generate electromagnetic waves, which cause the enhancement and decay of energetic electrons in the inner magnetosphere. While the importance of resonant wave-particle interaction has been demonstrated in recent studies, the linkage with solar wind structures and the appropriate way of incorporating global plasma wave distribution into radiation belt simulation are not quantitatively addressed yet. The objective of this proposal is to quantify the radiation belt electron acceleration and loss due to solar wind impacts using numerical simulations with state-of-the-art global plasma wave distributions as inputs. More specifically:
1. Apply the machine learning technique to reconstruct the global distribution and evolution of whistler mode waves (chorus, hiss, magnetosonic wave), electromagnetic ion cyclotron (EMIC) wave and ultra-low-frequency (ULF) wave in Earth's magnetosphere using solar wind parameters as inputs;
2. Use the global wave distributions reconstructed by the machine learning technique as inputs to a physics-based radiation belt model to analyze relativistic electron acceleration following strong solar wind activities, quantify the simulation uncertainties and compare with the simulation using empirical wave models as inputs;
3. Model the gradual transport and decay of relativistic electrons in the magnetosphere during the quiescent solar wind period using the same method as Objective 2.

Methodology

The machine learning technique has been developed to predict various plasma quantities including total plasma density and plasma wave amplitude in Earth's magnetosphere using controlling indices. We will extend this technique to predict the global distribution of whistler mode waves (chorus, hiss, magnetosonic wave), EMIC and ULF waves using solar wind parameters. The solar wind parameters are available from the OMNI data, and the dataset of various plasma waves and electron density are available from the THEMIS and Van Allen Probes measurements. We will use the Van Allen Probes observation of energetic electrons to analyze the radiation belt electron flux variations. After identifying typical events showing the electron response to the solar wind drivers, we will simulate the radiation belt flux evolution using the global plasma wave distribution predicted by the machine learning technique. The UCLA 3D diffusion code has been developed and fully validated for simulating the electron evolution due to resonant wave-particle interactions. For comparison, we will also perform the radiation belt simulation using the empirical plasma wave model, which is available from the recent satellite statistics. The simulation results will be validated against the satellite observations using validation metrics.

Proposed Contributions to the Focused Science Team Effort
This proposal directly addresses the Focused Science Topic 3 of NASA Living With a Star program, i.e., 'Understanding the Response of Magnetospheric Plasma Populations to Solar Wind Structures', and is highly relevant to the scientific objective 2, i.e., 'Understand how the Earth and planetary systems respond to dynamic external and internal drivers'. The communities of radiation belt research and space weather prediction will benefit from the proposed studies because this proposal demonstrates a feasible and state-of-the-art method in radiation belt modeling using upstream solar wind conditions as inputs, capable of quantifying and predicting radiation belt environment. Upon the completion of the proposed studies, we will provide extensive modeling efforts of Earth's radiation environment prediction with improved accuracy, contributing to the future space weather forecast.

Nariaki Nitta/Lockheed Martin Inc.
Improving Localization of the Source Regions of the Solar Wind

This proposal aims at better localization of the source regions of the solar wind observed in near-Earth space, by improving full-surface (synoptic) magnetic maps commonly used to compute macroscopic properties of the solar wind. We concentrate on updating the magnetic field in the polar regions. The solar wind is generally divided into two categories, fast and slow. We often associate the fast solar wind with coronal holes, dark regions in EUV and soft X-ray images. In comparison, there is hardly any consensus as to the origin of the slow solar wind. It is of vital importance to reliably locate the source regions in order to test the models of the solar wind. Knowing the source regions will also help us understand various properties of the solar wind, in terms of the properties of the source region. However, without the actual measurement of the solar wind very close to the Sun, we cannot directly locate the source regions. Instead, we have to depend on models that show where on the Sun we are magnetically connected to and thus exposed to the solar wind. These models generally require the radial component of the magnetic field of the full solar surface, i.e. a synoptic magnetic map, as boundary conditions. This is not observationally available.

Presently, the solar magnetic field is measured exclusively from the Earth. Only less than one half of the surface is adequately sampled by these measurements. We may use helioseismic farside imaging combined with STEREO EUV images to detect strong magnetic field regions on the backside. Magnetograms taken several days before or after may tell us whether there were indeed such regions on the backside, assuming that they would survive without drastic changes for several days. However, the polar regions are inherently very hard to observe from the ecliptic, and the historical measurements of magnetic field close to the poles may have large uncertainties. It is possible that these uncertainties may seriously impact our understanding of the magnetic connection between the Sun and Earth. In polar regions, the radial component of the field becomes almost perpendicular to the line of sight, and high-resolution and high-sensitivity vector measurements become essential.

We propose to improve synoptic maps that serve as the lower boundary conditions for models, simple and complex alike, by incorporating measurements of the vector field in the polar regions by the Hinode Spectro-polarimeter (SP) and SDO Helioseismic and Magnetic Imager (HMI). To date, SP is the best resource for the polar field due to its high spatial and spectral resolution. Inversions not included in the pipeline will be explored on SP data to ensure the best results for the polar regions. HMI is needed not only to correct for the SP pointing but also to address the time variability of the polar field. We will calibrate HMI data with SP, and use their radial field for updating the polar regions in the synoptic maps from HMI line-of-sight magneotograms. Using these maps, we run both the potential field source surface (PFSS) model and magnetohydrodynamic (MHD) model to locate the magnetic footpoint of the observer at L1 and estimate the uncertainties of the location. We will systematically conduct this study for periods selected on the basis of the difficulty of locating the source region of the solar wind. The proposed research should be an important part of FST#2, and will form the basis of other projects in the team whose emphasis may be the mechanisms of heating and acceleration of the solar wind.

Tulasi Parashar/University Of Delaware
Coupling electron and proton kinetic physics in the Solar Wind

Science Goals: The mean free path of particles in solar wind is ~1AU or larger, making it larger than most scales of interest. This implies that the solar wind is extremely weakly collisional. Lack of direct inter-species collisions drives the system into a highly non-equilibrium state where protons and electrons are not in a thermal equilibrium. However a lack of collisions and thermal equilibrium between different plasma species does not imply that the species do not affect each other. Both species affect the evolution and kinetic behavior of the other via electromagnetic interactions. However, which processes and channels enable this interaction, and the resultant effects have not gained much attention at all. It is our aim to develop a research program that addresses this problem using a combination of spacecraft data and kinetic simulations. The objectives of the proposal are: (I) Identify the channels of interaction between protons and electrons, and their relation to reconnection and turbulence in the solar wind (II) Identify the effects of this interaction on kinetic physics of both protons and electrons, (III) Create statistical surveys of correlations between various physical quantities of interest such as relative species heating, turbulence amplitudes, individual species temperatures, temperature ratio of both species, solar wind speed etc. The fundamental goal is to create a comprehensive knowledge base that can guide global simulations of solar wind to improve the thermodynamic representation of these species.

Methodology: The project will employ both, analysis of spacecraft data as well as kinetic simulations to address this problem. The strategy will be two pronged: (I) use kinetic simulations to identify the interaction channels between the two species, and quantify their roles. (II) Use spacecraft data to perform surveys of statistical correlations between various quantities of interest, and to identify specific intervals of interest to simulate using kinetic simulation models. For kinetic simulations, primarily fully parallel electromagnetic kinetic code P3D will be used. Our team has used this code extensively for studying turbulence and reconnection. For spacecraft observations, solar wind data from Wind, ACE, Cluster, Helios, and MMS spacecraft will be used. Single-spacecraft and multi-spacecraft techniques will be used where appropriate. Our team has expertise in analyzing data from all these spacecraft for various turbulence studies.

Proposed Contributions to Focused Science Team Effort: The interplay of protons and electrons in a collisionless system is of interest on its own at a fundamental level. However, the statistical correlations found in this study will be important to empirically represent the thermodynamics of protons and electrons in global models. A preliminary attempt in this regard has already been made by our collaborator Arcadi Usmanov by incorporating results from one of recent papers into his global heliospheric model. Moreover, the insights gathered from this study will help interpret and analyze data from NASA/ESA missions such as Parker Solar Probe, and Solar Orbiter.

Relevance: The proposed study is directly relevant to LWS program objective 1: "Understand how the sun varies and what drives solar variability" and Focused Science Topic 2: "Origins, Acceleration and Evolution of the Solar Wind". Understanding the interplay of proton and electron kinetic physics is central to a better understanding of the solar wind and its evolution. This study is also relevant to the first science objective defined in the 2014 Heliophysics Roadmap for NASA: "Solve the Fundamental Mysteries of Heliosphere" by understanding not only the fundamental processes that energize particles, but also by enhancing our understanding of the role that magnetic reconnection and turbulence play in the evolution of the solar wind.

Liying Qian/University Corporation For Atmospheric Research (UCAR)
Variability of global electric field and its impact on the longitudinal structure of the ionosphere

The global ionosphere electric field varies considerably longitudinally and from day-to-day, but the causes of these changes are not well understood. The main processes that produce electric fields include: the neutral wind dynamo; the high-latitude electric fields of magnetospheric origin and the penetration of these fields to lower latitudes. Interactions between these processes, their longitudinal variability, particularly during geomagnetic storms, produce highly dynamic yet poorly-understood, longitudinal and day-to-day variations in the global electric field. At the low- and equatorial latitudes, the global electric field can rapidly raise or lower the ionosphere, and thus help create or suppress plasma instabilities, generate small-scale irregularities that are deleterious to global positioning system (GPS) and radio signal propagation. We propose to improve our understanding of the variability of the global electric field and its impact on the mid-, low- latitude and equatorial ionosphere, by addressing four specific questions:

1) How do the lower atmosphere tides/waves and magnetospheric inputs impact the global electric fields during geomagnetically quiet times?
2) How do the quiet-time global electric fields impact the longitudinal and day-to-day variability of the ionosphere and plasma instability at the mid-, low-, and equatorial latitudes?
3) How do geomagnetic storms impact the global electric fields?
4) How do the storm-time global electric fields impact the longitudinal and day-to-day variability of the ionosphere and plasma instability at the mid-, low-, and equatorial latitudes?

We will employ the Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) to carry out the proposed work. An upper atmospheric model uses empirical or specified lower atmosphere tidal forcing. This impairs the accurate determination of electrodynamic forcing from both below and above. WACCM-X treats the whole atmosphere as an integrated system, and employs realistic electrodynamic forcing from both below and above. Periods of geomagnetic activity that are suitable for this study will be identified. WACCM-X will be run with, and without, magnetospheric inputs to understand the interplay between the two forcing sources. Ionospheric Rayleigh-Taylor (R-T) instability growth rates will be calculated using model outputs. The WACCM-X runs will be compared with data from Incoherent Scatter Radars (ISRs), Communication/Navigation Outage Forecast System-Coupled Ion Neutral Dynamic Investigation (C/NOFS-CINDI), the Defense Meteorology Satellite Program (DMSP), Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), and Total Electron Content (TEC), to understand longitudinal variations of the ionosphere and plasma instability from mid- to equatorial latitudes. Diagnostic analyses will be conducted to understand physical sources that drive this variability.

The project team will make the following contributions to the wider team effort. Model output and results from the proposed studies, including the calculated R-T instability growth rates, will be made available to all teams. We will attend team meetings and participate in team collaborative tasks.

The proposed studies directly address the LWS Focused Science Topic Mid-latitude and Equatorial Dynamics of the Ionosphere-Thermosphere System . It also addresses the Key Science Goal #2 outlined in the current NASA decadal survey: Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs . Furthermore, it is very relevant to interpreting the output from the current NASA flight mission, the Global-scale Observations of the Limb and Disk (GOLD). GOLD is seeing many structures in the equatorial anomalies after dark (R. Eastes, private communication), which can only be interpreted with a better understanding of the low latitude electric field.

Ludger Scherliess/Utah State University
Stormtime Longitudinal Variability in the Ionosphere-Thermosphere System

Science Goals
The primary science goal is to determine the longitudinal variability in the 3-D ionospheric density from equatorial to mid latitudes before, during, and after geomagnetic storms and to elucidate its relationship with associated changes in the neutral and ionospheric dynamics. A second goal is to determine the impact of longitudinal variations in the plasma and neutral environment on low-latitude ionospheric irregularities and plasma instabilities, and its relationship with their climatological occurrence and their occurrence during specific cases.

Objective 1: Collect a value-added database of global space- and ground-based I-T observations before, during, and after selected geomagnetic storms, including the entire year of 2012. The datasets will include TEC from ground and space receivers, occultation data from satellites , measurements of ionospheric irregularities from ground and space, ground-based ionosonde, Fabry-Perot, magnetometer, and radar observations, space-based wind, plasma density, and UV measurements.

Objective 2: Conduct ensemble simulations with our physics-based data assimilation (DA) models to determine the I-T response before, during and after geomagnetic storms. Our focus will be to specify the longitudinal variability of the low- and mid-latitude plasma density during geomagnetic quiet and disturbed times as well as the associated longitudinal differences in the neutral winds and plasma drifts, including longitudinal variations of disturbance dynamo and penetration E-fields.

Objective 3: Specify the relative roles of neutral and plasma dynamics at low and middle latitudes during varying storm phases in generation of longitudinal variability of the storm-time plasma distribution. The investigation will utilize MEPS model specifications of the electric fields, neutral winds and composition, together with our suite of physics-based Ionosphere-Plasmasphere Models (IPMs).

Objective 4: Evaluate the effect of longitudinal variations in the plasma and neutral environment that enhances or suppresses low-latitude ionospheric irregularities and plasma instabilities, and compare with climatology as well as specific cases.

Methodology
We will use a Multimodel Ensemble Prediction System (MEPS) for the I-T system. MEPS will incorporate selected members of the six data assimilation models with different physics, numerics and initial conditions. MEPS will provide specifications of the plasma density as well as the neutral and plasma dynamics, which will be used to identify the longitudinal structure of the I-T system. MEPS specifications of the plasma drift and neutral wind and composition will be used in our physics-based models to evaluate their relative role in the generation of longitudinal variations in the plasma density. This methodology is based on the success of the MEPS DA models that have been used in simulations and publications, including studies of SEDs, the deduction of lunar tides, the Weddell Sea anomaly, global-scale mid- and low-latitude ionospheric disturbances during storms, etc.

Uncertainties
The MEPS approach will identify which outcomes are model independent together with estimates of the model uncertainty provided by the spread of the individual model runs about their mean value. Furthermore, detailed validation efforts will be undertaken to establish the uncertainties of our results by comparing with independent data using various metrics.

Proposed Contributions to the Focus Team Effort
Our investigation to elucidate the longitudinal variability in the I-T system from equatorial to mid latitudes before, during, and after magnetic storms along with the associated changes in the neutral and ionospheric dynamics is relevant to the I-T science topic and directly addresses several goals of this FST. The value-added storm- and quiet-time global I-T datasets and the output from our ensemble DA runs will be made available to all Focus Team members.

Philip Scherrer/Stanford University
Linking Active Regions and Solar Cycles to Understand How Variable Flows in the Solar Interior Affect Surface Magnetic Field Evolution

Understanding the solar cycle is a fundamental and important scientific goal central to NASA's Heliophysics Division. Activity cycles differ substantially from one to another in various ways: the overall amplitude of magnetic activity, the timing of polar field reversal, and the asymmetry of magnetic properties between the northern and southern hemispheres. These observed properties are the result of interactions between magnetic fields and flows throughout each sunspot cycle. Such interactions are often subtle, but they play a key role in addressing questions of solar cycle activity and in improving cycle predictions.

Several studies during the SDO/HMI era have revealed correlations between variations of the poleward transport of photospheric magnetic fields with properties of both magnetic field in solar active regions as well as their decay products (Zhao et al. 2014; Sun et al. 2015). Features such as poleward surges often play an outsized role in advecting flux away from the activity belts. These studies therefore raise the question of whether predictions of indicators, such as the strength of solar-minimum polar fields, can be better constrained as a result of these relationships.

To this end, we propose to (1) better characterize the time-evolution of the near-photospheric, large-scale, zonal and meridional flow measurements, as inferred from helioseismology; and to (2) use these measurements to constrain the evolution of surface magnetic fields using a fast-running surface-flux transport (SFT) scheme of (Schrijver & DeRosa 2003). Uncertainties of the flow profile and the SFT model are well estimated. A primary goal will be to determine the effects of these flow profiles on the evolution of emerging magnetic flux and the resulting sunspot-cycle activity properties. Ensembles of flux transport models will be run to better determine the robustness of these results.

We anticipate that the proposed study of solar interior flows and surface flux evolution investigation will nicely complement the activities of the broader Focused Science Team. Importantly, we will provide to the Team improved, observation-based, active-region-modulated, time-dependent meridional and zonal flows, which are known to be a key constraint on all numerical models and dynamo theories. Additionally, we will be able to quickly model the effects of any time-evolving differential rotation and/or meridional circulations on the transport of flux across the photosphere.

The proposed work uses data from current and historical NASA spacecrafts, SDO and SOHO, together with numerical modeling, to establish the linkages of flows, polar field, and solar active regions, and to forecast solar cycles. This is highly related to one of the high level science goals from the Heliophysics Decadal Survey: Determine the origins of the Suns activity and predict the variations in the space environment. This is relevant to the scientific objectives of the Focused Science Topic (FST) 4 in this LWS program, to ``advance our understanding of the time-variable and large-scale internal solar dynamics, magnetic field creation, and emergence." This also fits into the ``overarching goal of the FST" that is ``to produce a data-driven model for solar magnetic flux production to enable forecasting of active latitude and longitude regions on time scales ranging from years to decades. The capability of predicting next solar cycle maximum provides matrix for measuring success for this investigation.

Lisa Upton/Space Systems Research Corporation
Improving Long Term Forecasts of Solar Variability with the Advective Flux Transport Model

The photospheric magnetic field drives the solar wind and produces space weather events such as solar flares and CMEs. The Advective Flux Transport (AFT) model combines data assimilation with the observed surface flows to accurately reproduce the evolution of the field. AFT uses an evolving convection pattern to produce realistic surface magnetic field maps (including a magnetic network). AFT can also incorporate synthetic Active Region (AR) data to perform experiments and make reliable predictions of the magnitude and timing of solar cycle properties.
Goals and Objectives
- Perform feature tracking of magnetic data to obtain surface flows and their residuals.
- Perform feature tracking on faculae to measure flow velocities of these features.
- Compare the measured flow velocities to access the uncertainty and improve estimates of the surface flows, particularly at latitudes above 75 degrees.
- Investigate relationships between the long-lived convective cells and the magnetic field.
- Provide an ensemble of predictions for Solar Cycle 25.
Methodology
We will use two distinct codes to measure the surface flows. Rightmire-Upton et al. tracked the magnetic patterns in SDO/HMI magnetograms to measure the axisymmetric Differential Rotation (DR) & Meridional Flow (MF). Recent improvements allow the code to more accurately measure the surface flows, particularly at high latitudes. We will use this improved code to measure the surface flows and their residuals (e.g. the torsional oscillations) for the entire MDI and HMI time periods.
Recently, the SWAMIS magnetic feature tracking code was used to measure DR & MF of individual magnetic features. We will adapt SWAMIS to track faculae in HMI continuum images. Faculae are magnetic structures that have increased visibility near the limb. We will compare the flows obtained where magnetic features and faculae overlap to develop an understanding of the uncertainty present in measurements of the faculae-derived flows.
Measurements of the surface flows explicitly include measurements of uncertainty both in the measured flow and in the fit parameters. We will quantify any systematic differences among our methods, and incorporate that knowledge into our reports of the measured flows.
Large-scale cellular flows (giant cells) are signatures of the internal dynamics of the the Sun s convection zone. They have been detected using the motion of supergranules and also with helioseismology. The detected structures are large, long-lived, and have the expected kinetic helicity and R large structures, axisymmetric flows, and the magnetic field.
AFT is a robust surface flux transport model that incorporates magnetic sources by manually inserting ARs or by assimilating magnetograms. Manual insertion allows AFT to investigate flows and make predictions, while assimilation produces accurate synchronic maps of the entire Sun. We will use AFT in assimilation mode to provide near-real time maps of the entire solar surface. We will use AFT in predictive mode to

create multiple realizations of the Cycle 25 evolution and predict the timing of the polar field reversals and Cycle 25 maximum.

Proposed Contributions to the Focus Team Effort

Our study is relevant to the FST scientific objectives. We will provide improved forecasts of the photospheric magnetic field on timescales from months to years. Our contributions include Novel data analysis techniques; Use of feature finding algorithms; Observational studies of the spatial and temporal structure of solar surface flows; and Studies to develop assimilative methods. Our metrics of success will be a) the degree to which our high-latitude results are self-consistent, and agree with the internal & surface flows derived by other teams using helioseismology; b) the degree to which previous solar cycles (and Cycle 25) can be predicted.

Haimin Wang/New Jersey Institute Of Technology
Study of Global-Scale Surface Flows and Migration of Polar Crown Filaments of the Sun in Past 10 Solar Cycles in Comparison with Helioseismology Results in 2 Recent Cycles

Scientific Objectives: In response to the FST call of "Understanding Global-scale Solar Processes and their Implications for the Solar Interior", we propose to combine surface flow measurements and helioseismology inversion to derive the meridional flows, differential rotation and zonal flows in multiple solar cycles, as well as their connection with other signatures of the solar dynamo, such as filament distribution/migration. We focus on two specific science issues: (1) Provide global flow measurements as input for dynamo and solar cycle modeling. The derived pattern of filament migration can be used for the validation of models. (2) As our study covers 10 solar cycles, we will investigate the effects of global-scale flows and polar crown filament migrations on different amplitudes of solar activity.

Methodology: In addition to the analyses of HMI and MDI data, NJIT group has digitized and will analyze full-disk Halpha images from 1956 to 2000 obtained by National Solar Observatory (NSO) and Big Bear Solar Observatory (BBSO) with a nominal cadence of 1 minute. All data are publicly accessible. Independently, co-I Institute Kodaikanal Observatory of Indian Institute of Astrophysics has digitized daily Halpha and Ca~K images since 1914, extending synoptic data to 105 years. From 2000 onward, we are also obtaining 1-minute cadence full-disk Halpha images with the 8-station Global Halpha Network (GHN), which has become an important resource for the solar physics community. We will focus our research on two key science topics using this unique data set in combination with modern NASA satellite data, aiming at understanding global-scale flows and linked magnetic properties of solar cycles.

(1) We will track the flows using features from Halpha images as proxy for magnetic features. The most important components include differential rotation, meridional flows, and zonal flows, which are closely related to the dynamo signature of solar cycles. We understand that advanced observations of SoHO and SDO provide better image quality

for this purpose; however, their data are limited to cycles 23 and 24, which may be atypical in respect to relatively low level of activity. The 1-minute cadence Halpha data cover 6 recent cycles (19 to 24) of various activity amplitudes. The recent two cycles will be compared with flow tracking results of SOHO/MDI and SDO/HMI data as validation and quality control. Helioseismologic data analyses in cycles 23 and 24 to be carried out by the Stanford group will derive near and sub-surface global flows to be compared with surface flow tracking in Halpha. Derivation of flows of cycles 15 to 18 will be attempted, but with much lower accuracy.

(2) We will study long-term variation and properties of filaments that carry important information on the magnetic signature of the solar cycles. Daily images will be sufficient for this purpose, therefore the study covers nearly 10 solar cycles. We will emphasize the study of the statistical and cycle dependent properties of filaments. In particular, polar crown filaments are related to the interface between new and old solar cycles. Their migration and disappearances may indicate underlying physics of solar cycles.

Significance: This is a joint effort of NJIT and Stanford group to combine the expertise in surface flow tracking with helioseimology inversion to understand evolution of the global-scale flows, filament migration, and potential sub-surface effects over nearly 10 solar cycles which matches the key goal of this FST. Therefore, our study will be highly relevant and importance to this FST. The team has developed most of the data analysis tools such flow tracking, helioseismology inversion, filament identification and characterization. Therefore, the study is feasible and low-risk. The detailed relevance will be elaborated in box 33 of Program Specific Data: Proposed Contribution to the FST Effort.

Qian Wu/University Corporation For Atmospheric Research (UCAR)
Investigating Penetrating Electric Field Effect on the Vertical Ion Drift

The scientific question for this proposal: what is the penetrating electric field effect on the equatorial vertical ion drift? During substorms, the high-latitude penetrating electric field moves equatorward, affecting the mid- and low-latitude ionosphere. It is well known that the penetrating electric field can change the equatorial vertical ion drift [Basu et al., 2007]. The goal is to understand how the penetrating electric field is linked with the equatorial vertical ion drift. We also would like to know sources of longitudinal variations in the vertical ion drift, which could include non-migrating tides and planetary waves.

We plan to use the LTR (LFM-TIEGCM-RCM) model to investigate the penetrating electric field effect on the vertical ion drift. Wang et al. [2008] showed that only a directly coupled magnetosphere and ionosphere model was able to simulate the penetrating electric field effect on the vertical ion drift. LTR is the latest directly coupled magnetosphere and ionosphere model. We will also use more realistic lower boundary conditions in the LTR to simulate the effect of the tides on the vertical ion drift in the low latitudes. Non-migrating tides introduce longitudinal variations in the vertical ion drifts, which can affect the occurrence of plasma bubbles. We plan to conduct a vigorous validation effort. We will use vertical ion drift and electron density observations from C/NOFS (Communications/Navigation Outage Forecasting System) and DMSP (Defense Meteorological Satellite Program) to validate the simulations. Differences between the model and observations will be compared with observation errors. In addition, we will use the GOCE (Gravity field and Ocean Circulation Explorer) thermospheric wind data to track traveling atmospheric disturbances from high to low latitudes.

We will provide LTR simulations to the team. We can also provide C/NOFS observation analysis, ground-based ion drift and thermospheric wind observations, and satellite observations from DMSP and GOCE Our team has long experience with NCAR models and is also very familiar with C/NOFS and DMSP with many publications. Our team can provide robust validation not only for our simulations but also for other team members.

Shasha Zou/University Of Michigan, Ann Arbor
Multi-instrument observational and modeling study of equatorial to mid-latitude ionosphere-thermosphere dynamics during geomagnetic disturbances

Our proposed study directly addresses the goal of the first FST topic: to understand mid and low latitude plasma density structure that affects scintillation as well as TEC variability and to accurately model the physical sources that drive it. In the equatorial and low latitude ionosphere, the equatorial ionization anomaly (EIA) is the most striking large-scale phenomenon. Embedded within EIA are low-density smaller-scale structures, i.e., the equatorial plasma bubbles (EPBs), which occur preferentially over the post-sunset local times. EPBs are known to host ionospheric irregularities that can cause severe satellite signal scintillations and even signal loss of lock, thereby affecting communication and navigation. However, our understanding of the day-to-day and longitudinal variability of EIA and EPBs is still illusive and thus prohibits forecasting capabilities.

During geomagnetic disturbances, energy and momentum from the solar wind and the magnetosphere largely deposit in the high-latitude region, while their impact can propagate to the mid-latitude to equatorial regions in multiple ways, including prompt penetrating electric field (PPEF), disturbance winds and the associated dynamo electric field (DDEF), and traveling atmosphere disturbances and their ionosphere manifestations (TADs/TIDs). In recent years, the rapidly developing ground-based GNSS receiver network has enabled regional to continental scale measurements of the ionosphere and has revealed rich dynamic structures in those regions during storm time, such as much widened or asymmetric EIA crest and super equatorial plasma bubbles reaching relatively high latitudes.
The overarching science goal of this proposal is to deepen our understanding of various factors affecting the EIA and EPB growth during geomagnetic disturbances and their contributions to day-to-day and longitudinal variability using a comprehensive

observational instrument suite and state-of-the-art numerical models. Specific science questions that this proposal aims to address include:

1. What are the relative contributions of different factors in determining the linear Rayleigh-Taylor (R-T) growth rate of EPBs, including PPEF/DDEF, meridional wind, and TADs/TIDs?
   a. How do those contributions change at different local times?
   b. What are the roles of TIDs/TADs in affecting the low- and mid-latitude ionosphere structures, including their interactions with EIAs, and possible impact on EPBs?
2. It has been reported that EPBs can extend to higher latitudes than theoretical expectation. Is it possible and how can they extend to such high altitudes?
3. How does the onset time of geomagnetic disturbances affect the longitudinal variation of EPBs occurrence and strength?

We propose to use state-of-the-art physics-based numerical models coupled within the Space Weather Modeling Framework (SWMF), including the recently integrated SAMI3 model and several other existing models, e.g., GITM, CIMI, RCM and BATSRUS, as well as multiple space-borne (C/NOFS, TIMED, DMSP, Swarm, GOLD), and ground-based (GNSS TEC, ionosondes and radars) instruments to address the science questions outlined above. We will carry out multiple real event simulations as well as idealized simulations and conduct systematic data-model comparisons to unravel the complex non-linear nature of the various phenomena.