

**Living With A Star Program (LWS21)**  
**Abstracts of Selected Proposals**  
**(NNH21ZDA001N-LWS)**

Below are the abstracts of proposals selected for funding for the Living With A Star Program (LWS21). Principal Investigator (PI) name, institution, and proposal title are also included. Sixty-six (66) proposals were received in response to this opportunity. On April 27, 2022, twenty (20) proposals were selected for funding.

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**Cynthia Cattell/University Of Minnesota**

**Investigating the radial evolution of the interactions between solar wind plasma, macroscopic structures, and intermediate frequency waves**

One of the key problems in developing accurate models for predicting space weather is understanding the co-evolution of waves and particles with solar radial distance. The coupled processes modify the temperature, energy and momentum of solar wind plasma, which are critical parameters for determining the interaction of the solar wind with the Earth's magnetosphere, and, ultimately how changes in the Sun impact life and technology. Our overall science goal is to determine nature of the interactions between intermediate frequency waves and large-scale solar wind structures and electrons and ions as they stream away from the Sun. We define intermediate frequency waves as approximately the range from the lower hybrid frequency to the ion plasma and electron cyclotron frequencies. We will concentrate on the evolution between  $\sim 15$  solar radii (reached by Parker Solar Probe during encounter 8) and  $\sim 1$  AU.

To address our science goal, we will focus on these specific questions:

1. What is the interdependence between intermediate frequency waves and large-scale structures including interplanetary shocks and stream interaction regions?
2. How do the occurrence, properties and dominant instability mechanisms of intermediate frequency waves depend on distance from the Sun?
3. How do the changes in dominant wave modes impact the evolution of electrons and ions?
4. Near 1 AU, how do these waves depend on solar cycle?

Technical approach: We will utilize in-situ plasma and waves data from spacecraft at varying distances from the Sun to examine wave properties and occurrence rates, and their relationship to electron and ion properties. We will focus on data from Parker Solar Probe, STEREO and Wind. As necessary to increase statistical significance or to examine regions farther from the Sun, we will use data from Solar Orbiter, Cluster, ARTEMIS, Cassini, and Juno. Waveform capture data provide the most detailed information on wave



modes and properties, while on-board spectra and bandpass filter data yield the continuous (or longer duration) observations needed to accurately assess occurrence rates and radial dependence. STEREO and Wind provide data over multiple solar cycles to assess changes in the waves and particles with solar cycle at  $\sim 1$  AU. We will utilize cold and warm plasma dispersion relation solvers, and fully kinetic simulations (FKS) simulations to determine instability mechanisms. Both particle tracing codes and (FKS) simulations will be used to assess the interactions of the waves with particles. Errors in data sets and data analysis and in theoretical techniques will be addressed.

Relevance to goals of LWS and of FST 3: Our science objective and questions are directly relevant to FST 3, specifically to the goals to understand (1) the physical processes driving the formation and propagation of solar-wind structures throughout the heliosphere and their variability with the solar cycle and (2) how the solar magnetic field and coronal structure determine the plasma and magnetic-field conditions in the inner heliosphere throughout the solar cycle." As described above we will establish how solar wind particles interact with intermediate frequency waves at different distances from the Sun, and, in addition, the solar cycle dependence around 1 AU. Our contribution to the Science Team effort will be providing a detailed understanding of the physics of intermediate frequency waves, their role in the radial evolution of solar wind plasma, and interactions with macroscopic solar wind structures. The insights we develop will be important for other teams, for example those who are examining MHD turbulence, the connectivity of solar wind structures to the solar corona, and evolution of the solar wind to the outer parts of the heliosphere. The new understanding that will be obtained through our research is needed to develop accurate predictive models for space weather, thus safeguarding life and technologies.

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**Rohit Chhiber/University Of Delaware**

**The Influence of Structure and Turbulence on Coronal and Heliospheric Dynamics - Improved Magnetohydrodynamic Modeling with Data-driven Subgrid-scale Effects**

The solar wind is a complex and dynamic system that involves interactions across multiple physical and temporal scales. Global magnetohydrodynamic (MHD) simulations coupled to subgrid-scale turbulence models incorporate such cross-scale couplings, and are a valuable tool for providing context for in situ observations and for studying a variety of problems that involve the interplay between large-scale structure and turbulence. A crucial input to these models is provided by solar photospheric magnetograms. However, models, which typically have relatively coarse resolution, are unable to utilize the full information available in high-resolution (hi-res) magnetograms. Here we propose a novel approach for extracting high-wavenumber information from these magnetograms and incorporating these data in our simulations. This will expand the physics contained within the model and help us better understand the magnetic field's influence on coronal and heliospheric structure and dynamics.



In particular, we propose the following focused research tasks -

- 1) Use a novel approach to estimate magnetic turbulence levels at the photosphere, by applying filtering methods on hi-res magnetograms to compute small-scale fluctuations.
- 2) Use these turbulence levels as data-driven, spatially-varying input for our model, which will produce distributions of large-scale fields and turbulence parameters through the inner heliosphere, thus enabling investigation of effects of photospheric turbulent variations on acceleration, heating, and dynamics of the inner-heliospheric plasma. Simulation results will be compared with in situ observations, to test model performance and provide 3D context for observations.
- 3) Apply the model to study magnetic field-line random walk (FLRW), and its effect on magnetic connectivity between solar sources and heliospheric observation points. Statistical approaches will be used to study FLRW, and evaluate related effects on field-line path-lengths and meandering in longitude/latitude. Implications for energetic particle transport will be considered.
- 4) Apply the model to study azimuthal flows in the young solar wind, including investigation of the effect of turbulence on angular momentum loss of the Sun, and on the morphology of the Alfvén surface. This problem is of particular contemporary relevance in light of recent observations [1] of unexpectedly strong azimuthal flows by Parker Solar Probe (PSP).

By linking a novel analysis of photospheric turbulence to the dynamics of the extended solar atmosphere, and by applying our model to the focused problems listed above, we aim to arrive at an improved understanding of the magnetic field's influence on the heliosphere, as well as the radial evolution of magnetic connectivity.

**Methodology:** We will use (and improve) well-tested 3D MHD simulations of coronal and solar wind that include turbulence modeling [2]. Effects of long-term solar variability will be incorporated by varying source dipole tilts and by using magnetograms (e.g., ADAPT, HMI) from different epochs. In situ observations from several missions, including PSP and Solar Orbiter, will be compared with the model. Standard diffusion-theory approaches will be used to study FLRW.

**Relevance to FST:** The proposed research will support FST#4 by achieving an improved understanding of the structure, evolution, and influence of the magnetic field from the solar photosphere to the inner heliosphere, focusing in particular on the interplay between turbulence and large-scale dynamics. 3D distributions of large-scale flow and turbulence parameters from our model can potentially be used to provide global context for more local investigations by other teams.

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[1] Kasper et al., *Nature*, 576 (2019); [2] Usmanov et al., *ApJ*, 865:25 (2018)



**Xiangning Chu/University Of Colorado, Boulder**

**Understanding plasmaspheric refilling: an investigation using machine learning models and physics-based simulation**

**Science description**

The plasmasphere consists of cold plasma ( $\sim 1$  eV) at mid- to low- L-shells surrounding the Earth. The plasmaspheric density and composition strongly influence energetic particle scattering and acceleration, wave propagation, wave-particle interactions. Therefore, it is essential to understand the plasmaspheric dynamics, i.e., the plasmaspheric erosion and refilling under various geomagnetic conditions. However, previous studies are limited by the lack of in-situ satellite measurements of the cold plasma at ideal locations and at any time. For example, satellite measurements following the motion of flux tubes are essential but missing how flux tubes are refilled. To resolve this issue, machine-learning (ML-) based models of the cold plasma, including total plasma density and different ion species, will be developed to provide global and time-dependent reconstructions of the cold plasma and ion species at any location (e.g., following any flux tube, or on the equatorial plane), and at any time (e.g., during the storm recovery phase). In addition, a physics-based model of the ionosphere, plasmasphere, and electrodynamics (IPE) will be compared to the ML-modeled semi-observations to aid in interpretation and study the mechanisms governing plasmaspheric refilling.

The main goal is to understand the typical characteristics and governing mechanisms of the cold electrons and ion species during plasmaspheric refilling using machine learning models and physics-based simulations.

The main objective is to answer the overarching science question: how are the cold electrons and various ion species refilled under different geomagnetic activity?

Specific science questions that will be addressed are:

1. How is the total electron density of the plasmasphere refilled?
2. How are the different ion species ( $H^+$ ,  $He^+$ , and  $O^+/N^+$ ) refilled?
3. What are the physical mechanisms controlling the refilling for each particle population?

**Methodology**

The proposed project will use in-situ data from the HOPE and EMFISIS instruments onboard NASA's Van Allen Probes; solar wind conditions and geomagnetic indices as driving conditions; machine-learning models of total plasma density and ion species, and physics-based IPE model. Specifically, to address:

- 1.Q1 and Q2: the refilling rates of the total plasma and ion species will be evaluated using the ML-modeled densities along flux tubes at different locations and different phases of geomagnetic activity.
- 2.Q3: the contribution of physical mechanisms will be evaluated using the physics-based IPE model, whose results will be cross-validated with and matched ML-modeled semi-observations.

The uncertainty of the ML-based model will be evaluated as a function of locations. The uncertainty of the IPE model will be quantified using sensitivity analysis.



## Relevance

Our study focuses on the cold plasmasphere and its drainage plume, which is the targeted plasma population of the FST target. Our project contributes to FST #3, objective 1 (refilling of the plasmasphere, and factors controlling these sources), objective 2 (the evolution of the plasmasphere), and objective 4 (determination of the properties and controlling factors of the low-energy electron and ion populations) in section 3.2. Our study uses machine learning models and physics-based simulations, which fits the types of investigation in section 3.3. The ML-based models will contribute semi-observations with uncertainties to the FST team, which serves as a comparison basis to validate first-principle models. The IPE model will provide the evolution of cold electrons and ions species in the plasmasphere under different geomagnetic activities. The metrics of success will be the model performance of the empirical model and IPE model. The milestones include the development of the ML-based model, model application to event studies, and comparison to the IPE model to understand the physical mechanisms of plasmaspheric refilling.

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**Shantanab Debchoudhury/Embry-Riddle Aeronautical University, Inc.**

## **Ionospheric responses to thunderstorm-generated acoustic and gravity waves over the continental US**

Intense convective systems like thunderstorms are known to generate acoustic and gravity waves (AGWs) that may reach ionospheric heights, induce complex dynamics, electromagnetic effects and seed self-evolving plasma instabilities and ionospheric irregularities including traveling ionospheric disturbances (TIDs). AGW detection and induced effects are routinely reported using ground- and space-based instrumentation. However, the characteristics of the AGW sources and the neutral and ionized background states along the path of AGW propagation, that facilitate the generation of detectable disturbances in the ionosphere, need to be understood and quantified. The continental US experiences significant thunderstorm activity in the summer months, with the mid-west identified as a global hotspot for convectively generated AGWs. This, along with the high density of suitable instrumentation, make it the perfect location for studying these phenomena. Our proposal attempts to study the dynamics, conditions and the extent of the impact of thunderstorm-generated AGWs on the mid-latitude ionosphere over the continental US. In particular, we propose to address the following science questions (SQs):

1. What are the solar, geomagnetic, and atmospheric and ionospheric conditions that lead to detectable TIDs from thunderstorm-generated AGWs?
  2. What are the amplitudes and temporal and spatial characteristics of TIDs occurring in the presence of thunderstorm activity?
  3. What are the momentum and energy depositions of thunderstorm-generated AGWs into the mid-latitude ionosphere and the related electrodynamic effects?
- To address SQs 1 and 2, we propose to use multi-layer observations for events associated with thunderstorm activity. Lower and middle atmospheric observations include NEXRAD radar reflectivity and rainfall rate maps to infer thunderstorm activity,



brightness temperature perturbations showing gravity waves in the stratosphere from the Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite, and data from the Cloud Imaging and Particle Size (CIPS) instrument on the Aeronomy of Ice in the Mesosphere (AIM) satellite. The impacts on the ionosphere will be studied using multi-constellation GNSS total electron content (TEC) observations and ground scatter from the SuperDARN radars that show evidence of irregularities like MSTIDs, as well as airglow imagers and available ionospheric satellite data. We will study the co-occurrences of ionospheric irregularities over simultaneous occurrences of thunderstorms, AGWs and TIDs, and create a database of events from 2010-2020, spanning the majority of Solar Cycle 24.

To address SQ3, we will perform a set of parametric and case-study modeling investigations with the use of our state-of-the-art full-physics-based three-dimensional coupled atmospheric and ionospheric models MAGIC and GEMINI, spanning the atmospheric and ionospheric dynamics from the ground to exobase heights. The simulations will include highly realistic specifications of thunderstorm-generated AGWs based on NEXRAD observations, and background atmospheric and ionospheric states based on empirical and climatological models and observations.

The science objectives of this proposal directly address the LWS 2021 solicitation and in particular Focused Science Topic (FST#1), which seeks to understand the impact of terrestrial weather on the Ionosphere-Thermosphere system. The proposed effort includes observational- and modeling- based study to address the variability in the ionosphere thermosphere mesosphere (ITM) system from upward propagating AGWs over convection sources. The science goals are directly applicable to the LWS Strategic Science Areas SSA-VI and SSA-VII and also aligns with the NASA Heliophysics Decadal Survey science goal 2, Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs".

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#### **Cooper Downs/Predictive Science Inc.**

#### **Linking Surface Magnetic Fields to the Structure and Dynamics of the Solar Corona**

We propose a focused, four-year study to understand the links between high resolution photospheric magnetic fields and the structure and dynamics of the solar corona. Our approach will be twofold: First pushing the boundaries of what is possible with data driven coronal modeling to understand how surface fields regulate magnetic complexity, heating, and plasma dynamics in the solar corona. Second, applying what we learn towards the practical interests and goals of the LWS program. In particular, we will focus on the following key questions:

1. How does the modeled coronal connectivity, heating, and plasma structuring change with the spatial resolution of the quiet Sun network and inter-network fields measured at the surface?



2. How does the evolution of these fields at the surface modulate coronal dynamics and connectivity across a range of spatiotemporal scales?
3. How do choices made in creating photospheric boundary conditions (observables, inversions, averaging) subtly influence our coronal solutions?
4. How can we better encapsulate subgrid" structure and dynamics in our simpler models of the global corona and inner heliosphere?

To address these questions, we will conduct focused experiments using a state-of-the-art MHD model of the global solar corona, driven by high-resolution measurements of the surface magnetic field. Our experiments, divided into a series of study arcs, will use extremely high-resolution patches within a global domain to understand out how and why small-scale structure and dynamics at the surface may influence not only the properties of the low solar corona, but the solar wind and inner heliosphere as well. Leveraging high-quality spectropolarimetric measurements of surface field distributions from Hinode/SOT and simultaneous measurements from SDO/HMI, we will also study how choices of observables, inversion methods, and spatiotemporal processing methods may subtly influence coronal model solutions. To complement our analysis of the physical processes occurring in the simulations and their differences from run to run, we will use magnetic field connectivity mappings and topological indicators to inform and interpret our results. We will also place our results directly into observational contexts by forward modeling extreme ultraviolet and white-light polarized brightness observables from SDO, STEREO, SOHO, and MLSO.

Our project is designed to address much of the stated scope of LWS FST 4: Towards a Quantitative Description of the Magnetic Origins of the Corona and Inner Heliosphere". We specifically target two of the three stated goals of the FST: aiming to better understand how magnetic connectivity evolves from the photosphere to the inner heliosphere and how the magnetic field drives coronal and heliospheric structure and dynamics. Our investigation is quite relevant to the stated context of the FST, being not only a physics-based study that connects surface-field distributions to the heliosphere, but one with a specific focus on how the properties of photospheric magnetograms, both vector and line-of-sight, might influence coronal and heliospheric models. This aspect, along with our aim to explore evolution and structure at higher spatiotemporal scales than previously possible---which may play an important but subtle subgrid role in our coronal and heliospheric models---has not only scientific relevance, but implications for practical modeling and key aspects of data/model uncertainty. Lastly, our project fits naturally within the larger Focused Science Team effort, as we will be well positioned to incorporate other potential surface field data products and methods in our modeling study, to forward model other remote-sensing or in situ measurements that may be of interest, and/or to provide helpful insights, data, or modeling products for related studies on these topics.

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**Philip Erickson/Massachusetts Institute of Technology**  
**Midlatitude topside ionospheric variations associated with plasmaspheric erosion and refilling**

The plasmasphere and ionosphere are a tightly coupled dynamic system. Plasmaspheric flows can produce nighttime midlatitude ionospheric anomalies. At storm main phase, plasmaspheric erosion temporarily depletes large regions due to enhanced sunward flow expanding equatorward, with subsequent refilling during storm recovery phase.

Ionospheric storm-enhanced density, with a magnetic dual in plasmaspheric plumes, appears to be uplifted and sometimes is situated within ion upflow regions. During the recovery phase, plasmaspheric refilling takes place principally via diffusion, established by balance between gravity and plasma pressure gradients. Ionospheric storm recovery creates a negative storm phase when reduced mid / low latitude thermospheric O/N<sub>2</sub> changes occur. These ionosphere-plasmasphere mass exchange processes have significant geospace impact including alteration of ion trajectories in the inner magnetosphere in the presence of cold plasma, extending the reach of these influences into magnetospheric configuration. Frequency of storm occurrence keeps this process inherently dynamic. Throughout, the topside ionosphere is a key and dynamic region. We will focus on the following science questions: (1) What are characteristic topside ionospheric variations associated with plasmaspheric erosion and refilling during geomagnetic storm main and recovery phases? (2) During plasmaspheric erosion and refilling, what is the influence of topside ionospheric dynamics on plasmaspheric and inner magnetospheric cold plasma populations? (3) What are controlling factors and physical processes in topside ionospheric recovery?

To address these questions, we propose 8 research tasks to analyze cold plasma density in the topside and other ionospheric altitudes, plasma temperatures, and thermospheric column O/N<sub>2</sub> to gauge dynamic and chemical processes which are important for topside ionospheric recovery. We will study cold plasma state parameters in the plasmasphere and inner magnetosphere, and establish linkage with topside ionospheric sources during the short-term storm main phase and long-duration recovery phase. We will also provide ionospheric upflow estimates in the topside, and gauge ionospheric storm recovery/plasmaspheric refilling.

Primary 2012-2019 datasets (with maximum data overlap) include DMSP and Swarm density and velocity, GNSS topside TEC from LEO satellites GRACE, TSX, Swarm-A, Swarm-B, and MetOp-A, and GUVI column O/N<sub>2</sub>. This will be augmented by Millstone Hill incoherent scatter radar observations as well as GNSS TEC and ionosonde observations. We will also use Van Allen Probes A and B measurements of inner magnetospheric cold plasma density, electric field, and cold ion composition and THEMIS A, D, and E inner magnetospheric measurements of cold plasma density. Our work will study topside ionosphere source plasma and in-situ cold plasma dynamics in the plasmasphere and inner magnetosphere, addressing FST SSA-V (Dynamics of the Global Ionosphere and Plasmasphere) and SSA-IV (Variability of the Geomagnetic Environment) and focusing on FST #2: the cold plasmasphere, drainage plume and refilling. Our LWS FST team contribution will include data and analysis of topside ionospheric recovery characteristics as a comparison basis for team validation of first-principle models with an ionospheric component. Joint analysis of topside ionosphere and



inner magnetosphere cold plasma configuration and dynamics will provide coincident information for these same models on plasma sources and evolution within the coupled ionosphere and plasmasphere (and inner magnetosphere).

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**Mei-Ching Fok/NASA Goddard Space Flight Center**

**Understanding the Sources, Recirculation, and Impacts of Cold Plasma with Self-Consistent Modeling**

Science Objectives:

- SO1. Understand the factors controlling the refilling rate of the plasmasphere.
- SO2. Follow the pathways of cold plasma from its source to the drainage plume, to the magnetotail and back to the plasmasphere region.
- SO3. Determine the impacts of cold plasma on reconnection rates and mass loading in the magnetospheric system.

The plasmasphere is the cold ( $< 10$  eV) plasma population that resides in the inner magnetosphere. It is well established that the plasmasphere provides the environment for the generation and excitation of various plasma wave modes. These plasma waves, in turn, serve as agents or avenues for cross-energy coupling between the ring current and radiation belt particles. Nevertheless, relatively little attention is given to quantify the sources of the plasmasphere particles. What are the controlling factors of the refilling rate? On the other hand, the fate of the plasmasphere particles that encounter the dayside magnetopause is also poorly understood. Are they just lost in the solar wind? What fraction of them re-enter the magnetosphere? Moreover, what fraction of these re-entered particles are transported back to the inner magnetosphere? Furthermore, what are the impacts of the cold plasma on the global magnetospheric system? How much does the drainage plume reduce the dayside reconnection rate and thus the efficiency of energy coupling between the solar wind and the magnetosphere? How much does the mass loading effect from the plasmasphere influence the dynamics of the global magnetosphere?

Methodology:

A combination of global simulation and data analysis will be employed to address our science objectives. In this investigation, a multifluid MHD code (Block-Adaptive-Tree Solar-wind Roe-type Upwind Scheme [BATS-R-US]) combined with a comprehensive inner magnetosphere-ionosphere (CIMI) model will be our main modeling tool. A plasmasphere model has been embedded in the CIMI model. The plasmasphere model calculates spatiotemporal plasmaspheric density distribution considering corotation, convection, daytime refilling, and nightside diffusion. In this investigation, the refilling rate will be estimated by the SAMI3 (Sami3 is Also a Model of the Ionosphere) model. Critical to this investigation is the recent inclusion of a separate plasmasphere fluid in the multifluid BATS-R-US code. That fluid is filled from the CIMI code based on its embedded plasmasphere model. Outside the CIMI domain, the plasmasphere fluid continues to evolve based on the MHD calculation. We thus are able to follow the cold



plasma from its source to the plasmasphere region and to the global magnetosphere. Our simulation results will be compared with observations. The main data sets that will be analyzed are the particle and field data from the NASA Van Allen Probes mission. The plasmasphere density can be inferred either from the upper hybrid wave frequency or from the spacecraft potential.

**Relevance:**

The proposed study is relevant to Focused Science Topic #2: Pathways of Cold Plasma through the Magnetosphere. The investigation directly addresses the Focused Science goals of understanding the sources, evolution, recirculation and impacts of the cold plasma in the magnetosphere. This investigation will improve our predictive capability of the temporal and spatial characteristics of the plasmasphere. Our investigation has significant space weather relevance since the plasmasphere region constitutes a safe haven for spacecraft surface charging. We will perform CIMI-BATS-R-US simulations for events selected by the Focused Science Team. We will also provide simulation support to the team as needed.

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**Konstantin Gamayunov/Florida Institute Of Technology**

**The source of warm plasma cloak due to ion heating by EMIC waves**

**Goal and Objectives:** Our overarching goal is to systematically investigate the source of warm plasma cloak due to heating of low-energy ions by electromagnetic ion cyclotron (EMIC) waves. To achieve this goal the following two objectives will be fulfilled. The 1st objective is to investigate in detail the individual cases of O<sup>+</sup> and He<sup>+</sup> heating and geomagnetic trapping due to dissipation of the He- and H-band EMIC wave energy, respectively. The 2nd objective is to produce the global geomagnetically dependent maps of the O<sup>+</sup> and He<sup>+</sup> heating and trapping parameters due to interaction with EMIC waves. On the global (MLT, L)-scale and during different geomagnetic conditions, we will quantify the energy and pitch angle ranges of ions interacting with EMIC waves, their densities, the energies per ion gained during EMIC wave events and the resulting increase of pitch angles, the observed distribution functions of those ions, and the concurrent EMIC wave and background plasma parameters including its ion fractions.

**Methodology:** There are two dominant bands of EMIC waves in the Earth's inner magnetosphere, where the He-band is the dominant one, which is followed by the H-band. The former band effectively heats low-energy O<sup>+</sup>, and the latter one heats He<sup>+</sup>. We will analyze all the He- and H-band EMIC wave events observed by the two Van Allen Probes from the beginning through the end of mission. For each event, all the needed wave and plasma parameters, DC magnetic field, and ion distribution functions will be taken from Van Allen Probes during the event. The observational data will be used to separately calculate the damping rates for He- and H-bands due to interactions with O<sup>+</sup> and He<sup>+</sup>, respectively. Our damping rate code will allow us to identify 1) the O<sup>+</sup> and He<sup>+</sup> energy and pitch angle ranges that contribute most in the damping rates, and so to integrate the observed ion distributions to get number densities of those ions. Then, using



the observed frequency spectra of EMIC waves and calculated damping rates, we will calculate 2) the wave energy dissipated during each wave event that gives us the energy per ion absorbed by the heated in the perpendicular to magnetic field direction O<sup>+</sup> and He<sup>+</sup>, and 3) the resulting increase of the O<sup>+</sup> and He<sup>+</sup> pitch angles that shows us whether an additional geomagnetic trapping of the upflowing ionospheric ions is produced by waves. Finally, using the results from all the individual cases analyzed, the global geomagnetically dependent maps of the wave induced O<sup>+</sup> and He<sup>+</sup> heating and trapping parameters will be produced.

Van Allen Probes Data to be Used: 1) EMFISIS to get DC magnetic field, the high-resolution magnetic field for waves, and electron number density estimated from the upper hybrid frequency, 2) EFW for electron number density estimated from spacecraft potential, and 3) HOPE to get distribution functions of O<sup>+</sup>, H<sup>+</sup>, and He<sup>+</sup> and also to estimate the ion fractions.

Relevance and Contributions to the FST: This effort will provide a better understanding of the warm plasma cloak sources by investigating its specific source due to heating of low-energy ions by EMIC waves, and so it is relevant to the FST #2: Pathways of Cold Plasma Through the Magnetosphere. The potential contributions of proposed study to this FST's effort are 1) a quantitative understanding of the source of warm plasma cloak due to ion heating by EMIC waves and 2) the global (MLT, L) and geomagnetically dependent maps of the O<sup>+</sup> and He<sup>+</sup> heating and trapping parameters due to interaction with EMIC waves that include the energy and pitch angle ranges of ions interacting with EMIC waves, their densities, the energies per ion gained during EMIC wave events and the resulting increase of pitch angles, the observed distribution functions of those suprathermal ions, a likelihood of an additional wave induced geomagnetic trapping of ions, and the concurrent EMIC wave and background plasma parameters including its ion fractions.

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## **Larisa Goncharenko/Massachusetts Institute of Technology**

### **Imprint of stratospheric QBO on the thermosphere and ionosphere**

#### Science goals and objectives

During the past decade or so, it has been established that the troposphere-stratosphere region drives ionosphere-thermosphere-mesosphere (ITM) variability through generation of a spectrum of vertically propagating waves, including planetary waves, tides, and gravity waves. It was also revealed that the stratospheric Quasi-Biennial Oscillation (QBO) is one of the significant sources of variability in the mesosphere and lower thermosphere (MLT). However, studies of the QBO signature in the ITM are challenging due to the complex nature of the sun-atmosphere ionosphere system. In particular, earlier studies of links between the stratospheric QBO and the ionosphere remain inconclusive due to similar oscillations in solar flux.

This project strives to identify and quantify the imprint of stratospheric QBO on the ITM. It is well known that changes in the middle atmosphere wind are associated with tidal



amplification and larger ionospheric variability during transient events such as sudden stratospheric warming. We hypothesize that stratospheric wind changes associated with the QBO produce tidal variability on QBO time scales and, consequently, are imprinted on ionospheric electron density. Moreover, the QBO-related variation in non-migrating diurnal tides in the MLT can modulate the equatorial ionospheric anomaly wave-4 longitudinal structure. Confirmation of this hypothesis will provide a basis for improved physical understanding of additional terrestrial sources of ionospheric variability, and it will have implications for the prediction of ionospheric conditions on short-term, sub-seasonal and interannual time scales.

### Methodology

We will use a combination of space-based and ground-based data to identify anomalies in the ITM that are associated with the westerly and easterly stratospheric QBO phases, and study impact of different QBO phases on the ITM variability. TIMED SABER and TIDI data will be used to determine impact of QBO on tidal amplitudes. Observations of O/N<sub>2</sub> from TIMED GUVI will be used to isolate QBO signatures in the ITM. We will develop localized empirical models of total electron content (TEC) and peak electron density at several latitude/longitude locations to form a broad grid, using 20+ years of data of GNSS TEC observations and multiple ionosondes. These models will be used to separate TEC/NmF<sub>2</sub> variations attributed to solar flux, season, latitude, longitude, and local time from variability induced by the stratospheric QBO. We will use NASA MERRA2 data products to examine the importance of several tropospheric and stratospheric parameters as independent drivers for empirical ionospheric models for multiple distinct low-latitude locations. In addition to standard linear regression models, we will use machine learning tools and investigate the use of nonparametric regression (e.g. Gaussian processes and neural networks) to formulate our empirical models and select the most appropriate set of terrestrial drivers for the final models. Simulations with WACCM-X constrained with MERRA-2 will be employed to interpret variability of tidal dynamics in the MLT region for different phases of QBO and their subsequent impact on the thermosphere and ionosphere.

### Relevance and Proposed Contributions to the FST Effort

This project is directly relevant to the scientific objectives of the FST, as it will identify and quantify the relative role of stratospheric QBO in the ITM variability on sub-seasonal and longer time scales. Our team will contribute unique capabilities to the FST effort: (1) Observations-based characterization of QBO in ITM parameters at low and middle latitudes; (2) Model-based understanding of driving mechanisms that cause QBO in ITM; (3) Numerous data sets, numerical simulations, and empirical models developed during the project will be provided to the FST team to enhance other studies.

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**Jia Huang/University Of Michigan, Ann Arbor**  
**The Alfvénic Slow Solar Wind Over Multiple Solar Cycles**

**SCIENCE GOALS AND OBJECTIVES:** The slow solar wind is of great value for further investigations in regard to both science and application concerns. In general, the slow solar wind shows low Alfvénicity, which measures the correlation of the magnetic field and solar wind velocity fluctuations. However, the Helios spacecraft recorded high Alfvénicity slow solar wind at around 0.3 AU from the Sun, and the observations suggest this kind of slow solar wind shares similar characteristics as the fast solar wind.

Following studies find the Alfvénic slow solar wind (ASSW) both at around 1 AU and in the inner heliosphere, and the results further indicate the ASSW and fast solar wind are similar in both macro and micro scales, implying the ASSW should also originate from the coronal holes. Additionally, the latest Parker Solar Probe (PSP) spacecraft has observed prevalent ASSW in the inner heliosphere, suggesting the ASSW could contribute to the network of slow solar wind. However, contradictory conclusions on the origin of ASSW are implied by different works, the reason could be the choice of different observations and/or the different methodologies. We note that most of previous works associated with the ASSW are mainly focused on the comparisons of different solar streams with several selected intervals or limited dataset, and there still lacks a comprehensive study of the ASSW with large dataset through different solar cycles to uncover the distributions, evolutions, and origins of the ASSW. Therefore, it is greatly valuable to investigate the ASSW over multiple solar cycles with multiple datasets. In this project, we want to focus on the following aspects:

" Distributions. We will identify the ASSW intervals in different solar cycles and build a large dataset with several spacecraft observations with a powerful machine learning technique. This dataset can give global distributions of the ASSW over several solar cycles. In this way, we want to show how the solar activities control the large-scale variations of ASSW with less uncertainty, and to identify how much the ASSW contributes to the slow solar wind at different phase of solar cycles.

" Evolutions. The Alfvénicity of solar wind will reduce with distances, so we observe less ASSW at 1 AU. Therefore, it is worth to investigate the radial evolutions of the ASSW.

" Origins. The limited dataset and different methodologies in the analysis of ASSW may bring uncertainties to identify the origins. Therefore, based on the large dataset, we plan to use both multi-event study and statistical method to compare the properties, especially the compositional signatures, of highly ASSW with other solar winds. Moreover, we will use the Potential-Field Source-Surface (PFSS) model to trace the ASSW back to the Sun. Combining the observations and model results, we want to figure out the origins of ASSW.

**MISSION DATA:** We will use the in-situ data from the Helios, Ulysses, Wind, ACE, PSP and Solar Orbiter. The combinations of multiple datasets over several solar cycles from the inner heliosphere to 1 AU can help study the ASSW thoroughly.

**METHODOLOGY:** Using the Helios, Ulysses, Wind, ACE, PSP and Solar Orbiter observations, we will first identify the intervals of the ASSW with machine learning



technique. In the following, we will investigate their properties and distributions with solar cycles. Then, we will compare the inner heliosphere observations with that at 1 AU to figure out the radial evolutions of the ASSW. Moreover, we will trace the ASSW back to the source regions with PFSS model. Finally, we will combine the model results with the compositional signatures to identify the origins of ASSW.

RELEVANCE: The proposed works on the Alfvénic slow wind over multiple solar cycles are highly relevant to the Focused Science Topics of the Living With a Star Science: Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle".

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**Bernard Jackson/University Of California, San Diego**  
**A Holistic Solar Cycle Approach to Heliospheric Evolution from UCSD 3-D Reconstructions Using Thomson Scattering Data from STEREO HI and SMEI Imagery, and Interplanetary Scintillation Observations**

From the year 2000, UCSD's time dependent three dimensional (3-D) reconstruction program has characterized the topology throughout the inner heliosphere based on interplanetary scintillation (IPS) observations. Now also incorporating Solar Mass Ejection Imager (SMEI), and STEREO Heliospheric Imager (HI), imagery and available in-situ measurements from any spacecraft, we have worked to combine all of these observations into a super-program" analysis system. This takes advantage of the benefits of each data source to provide plasma densities, velocities, and extrapolations of solar surface magnetic fields. Our Japanese colleagues have gathered much information about background global solar wind properties in the inner heliosphere using IPS analyses over two solar cycles. However, until now there has not been an attempt to reconstruct the propagation of rapid time variations much beyond Earth's orbit. Here we propose to rectify this and use our comprehensive 3-D reconstruction program to map structures globally to extend the recent science from Mars out to Jupiter. This effort is enhanced by ingesting these tomographic inputs into 3-D MHD modeling using ENLIL, so that now more of the known plasma physical properties are included to this solar distance.

From the UCSD Thomson-scattering SMEI and STEREO HI 3-D reconstructions of densities with about one hour cadence and few-degree latitude and longitude spatial resolutions near Earth and at STEREO, we have found that the heliosphere at 1 AU is not as simple as many modeling efforts imply. Our analyses show that CME fronts at 1 AU are highly corrugated and patchy; some have wavy fronts, and inhomogeneous structure. In-situ measurements can be adequately reproduced at a one-hour cadence, but nearby densities can be greatly different. This feature of the heliosphere, and the science of the small-scale propagation of switchback" fields and plasma, has become more evident from recent Parker Solar Probe (PSP) analyses. We do not know if such corrugation is a ubiquitous feature in all solar wind features - solar interaction regions (SIRs), shock processes, or the background solar wind. We assume that some smoothing occurs, and



that the solar wind in general becomes more homogeneous at the distances probed by Ulysses; this proposed effort will clarify this using our highest resolution data sets.

For this FST #3 effort, we will use archival SMEI, STEREO, and IPS data (from the year 2000) and will employ all extant NASA in-situ plasma monitors as input, and verification checks to beyond Jupiter's orbit. This will allow better scientific comparisons all the inner planets to Jupiter, and at the asteroids in between. We note that most members of our group are Co-investigators on NASA's Polarimeter to Unify the Corona and Heliosphere (PUNCH) Small Explorer (SMEX) mission; when remote-sensing data from PUNCH becomes available, and with agreement from NASA and members of the FST, we will incorporate these additional data into the tomography. Our analysis goals set out below will:

- 1) Assess the 3-D tomography data sets over time to determine the best IPS, SMEI, and STEREO HI imagery sets to use at different times. These optimal data combinations throughout the solar cycle will then be used as inputs to the ENLIL 3-D MHD model to augment the solar wind interaction science out to the distances of the two nearest planets beyond Earth's orbit.
- 2) With our new understanding that CMEs and presumably most solar wind structures are spotty or at least corrugated from near the Sun to Earth, we will refine the scale of this variability, and its change with solar distance, in our most highly-resolved data sets.
- 3) Where CMEs are first observed in the LASCO or STEREO coronagraph images by FST members, we will track them until they are measured in situ at Earth, Ulysses, STEREO, and more recently at PSP, Solar Orbiter, and BepiColombo, out as far as Mars, and Jupiter.

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### **Guiping Liu/University of California, Berkeley**

#### **Impacts of atmospheric planetary-scale waves on the equatorial ionosphere**

We propose to systematically investigate where and how tides and planetary waves from the lower atmosphere drive the longitudinal structures and day-to-day variations of the low-latitude ionosphere. Tides, such as DE3 excited by latent heat release in the tropical troposphere can propagate upward to the lower thermosphere, where they modify the wind-driven dynamo electric fields causing the ionospheric four-peaked structures. Although most planetary waves are trapped in the middle atmosphere, they may still extend their influences into the ionosphere. By modulating tides, the multi-day periodic signatures associated with planetary waves could be carried to high altitudes. In addition, fast (short period) planetary waves, such as the 3-day waves may propagate to the F-region, directly driving variations in the density and height of the ionospheric F-layer peak. Through various pathways, the lower atmosphere forcing contributes significantly to the large-scale variability of the equatorial ionosphere.

Previous studies have identified tides and planetary waves in the E-region (~100 km altitude), but the vertical extents of these waves and how exactly they impact the



ionosphere have not yet been determined due to lack of sufficient observations at higher altitudes. Here we will use newly obtained concurrent observations of both the atmosphere and the ionosphere from multiple data sources of ICON, GOLD, COSMIC-2, TIMED, Aura, COSMIC, and ground-based GPS that provide the necessary coverage. Our work will incorporate a systematic analysis of various tides (DE2, DE3 etc.) and planetary waves (2-, 3-, 5-, 6-day wave etc.) across a broad altitude range from ~90-300 km and simultaneously search for their corresponding signatures in the F-region ionosphere. These results will be compared to the simulation results from NCAR's Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X), including validating large-scale waves and their effects in the model. The WACCM-X results will be used to interpret the observed signatures and determine the processes responsible for tides and planetary waves to drive the ionospheric structures and variations.

Objective 1: Which tides and planetary waves are observed to strongly impact the equatorial ionosphere? At what altitudes do these waves exert their impacts on the ionosphere? We will analyze the observational datasets to identify each tide and planetary wave (characterized by period, amplitude, zonal wavenumber, vertical wavelength etc.) and the corresponding ionospheric structures and variations throughout multiple years from 2002-present. This will allow for identifying which waves and characteristics are influential. The ICON neutral wind data span both E- and F-regions, enabling observations of the altitude limits where these waves propagate.

Objective 2: Are there seasonal dependences for tides and planetary waves to strongly impact the equatorial ionosphere? What impacts do these waves have on the ionosphere at the solar minimum condition? These available datasets are adequate to identify tides and planetary waves and their ionospheric signatures in all seasons. Moreover, the ICON and GOLD data at the current solar minimum are extremely useful to examine the vertical propagations of these waves and their modifications on the ionosphere during quiet solar activities.

Objective 3: How do tides and planetary waves impact the structures and variations of the equatorial ionosphere? We will compare the WACCM-X simulations against the observations, and perform model runs with different resolutions and schemes to achieve the best model and observation agreements. We will analyze the model results to understand the pathways for tides and planetary waves to impact the ionosphere. Using controlled model runs, we will be able to quantify the contribution of each of the processes that are most significant to drive the ionospheric variability.

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**Mihailo Martinovic/University Of Arizona**  
**Non-linear Solar Wind Turbulent Heating from 0.08 to 5.2 AU**

Describing the heating of the Sun's corona and the expanding solar wind is a central problem of modern heliophysics. Several heating mechanisms have been proposed, each expected to operate under different solar wind conditions.

Recent results from Parker Solar Probe (PSP) have shown one particular non-linear mechanism - Stochastic Heating (SH), driven by magnetic moment invariance breaking due to turbulence, is increasingly effective at lower radial distances from the Sun.

Examination of the proton Velocity Distribution Functions (VDFs) below 0.25 AU during PSP Encounters 1&2 confirmed theoretical predictions for VDF shapes to change from standard Maxwellian to flattop distributions, as SH tends to primarily heat particles slower than the VDF thermal speed.

In parallel, recent results based on Helios observations have demonstrated that the level of ion scale turbulent fluctuations---regarded as another clear indicator of SH activity---steadily decreases with radial distance, while also being enhanced in fast solar wind, more frequently measured close to the ecliptic around solar maximum. However, the Helios ion analyzers did not have the resolution required to confidently identify the VDF shapes. As the turbulence contains the information about in situ solar wind conditions along with traces of its evolution from the Sun, there was no conclusive way to distinguish if SH was operating at the point of measurement, or observed fluctuations are a remnant of the heating that happened days ago closer to the Sun.

In this project, we will use combined 45 years long survey of VDF and magnetic field data from Wind and Ulysses, enhanced with new high-resolution PSP and Solar Orbiter (SolO) measurements (available at CDAWeb and ESA Solar Orbiter Archive), to answer three crucial science questions (SQs):

1. How levels of SH in the inner heliosphere vary throughout three solar cycles?
2. Is the measured SH a genuine in situ process or a trace of near-Sun enhanced heating?
3. Is SH accompanied and/or affected by linear instabilities?

The proposed SQs are relevant to the FST Topic #3 Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere and through the Solar Cycle", its Goal #1 Utilize long-term measurements to quantify how the solar cycle impacts in situ plasma and magnetic field of the inner heliosphere" and Measurement of Success #2 Understanding and quantification of the impact of solar cycle variability on solar wind structures in the inner heliosphere".

To answer SQ1, we will extend the existing Helios SH analysis to Wind and Ulysses by using our already developed computationally efficient algorithms. These results will explain the solar cycle dependency of SH at various heliographic latitudes.

To understand if the estimated SH is happening in situ (SQ2), we will perform a statistical study of VDFs measured by Wind and Ulysses to estimate if they indeed exhibit flattop shape when SH is expected to be the dominant heating process. Some of the streams measured by Wind will be downstream of PSP and SolO, which will add another level of confidence as the large-scale statistical study will be enhanced by smaller multi-point case studies of tracked streams.

Finally, time-frequency analysis of turbulence will allow us to upgrade previous investigations of SH by differentiating low-frequency turbulent power that drives SH



from coherent wave power, and investigate how SH is connected to plasma stability (SQ3). Using well established PLUME and ALPS dispersion solvers, we will be able to understand the profile of linear instabilities raised in regions where increased SH modifies the VDF, and quantify the energy transferred back from particles to fields via instabilities.

The described research will provide a confident, reliable model of the solar wind heating, bringing us closer to overall understanding solar wind thermodynamics throughout the solar cycle and at varying distances and latitudes.

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### **Jens Oberheide/Clemson University**

#### **Exploring the response of the ionosphere/thermosphere to the Madden Julian Oscillation**

The overarching science goals are to explore and understand the global response of the ionosphere/thermosphere (IT) system to the Madden-Julian Oscillation (MJO) in the tropical troposphere, particularly ionospheric plasma and drifts. We will comprehensively analyze the MJO modulation of tides, Ultra-Fast Kelvin Waves (UFWK) and the mean in neutral and plasma parameters using a variety of spaceborne assets (ICON, GOLD, COSMIC-2, TIMED), ground-based observations (Poker Flat Incoherent Scatter Radar), and investigate the physical coupling mechanisms into the IT system using dedicated SD-WACCM-X and TIEGCM simulations, and MERRA-2.

The MJO is a recurring tropical weather pattern that shifts low-latitude convection patterns on intra-seasonal time scales (30-96 days). Recent progress in neutral dynamics data analysis mainly from SABER/TIMED and MERRA-2 has unequivocally revealed that the MJO impacts tidal and GW activity in the upper mesosphere (80-100 km) on the order of 10-20%, depending on latitude, season, and MJO location. Similar effects have been found in Kelvin waves and in thermospheric density from in-situ satellite measurements (i.e., GOCE). The new COSMIC-2, ICON and GOLD data allow us to make the next step and explore how the ionosphere responds to the MJO, a challenge that could not be met before due to a lack of data to resolve wave and mean variations originating from the lower atmosphere on weather timescales. Consequently, the MJO-modulation of the ionospheric plasma and drifts is not known to date. It is, however, likely that a strong response exists due to the MJO in tides, UFWK and GWs that either (i) impart the signal on the ionosphere through E-region dynamo or (ii) direct upward propagation and/or composition changes.

The ICON precession rate is fast enough to diagnose the tidal spectrum (period/wavenumber) with a time resolution  $\sim 1$  month, which is sufficient to extract a MJO modulation of the tides in E-region winds and in F-region drifts & ion densities. This will be supported by high resolution SABER/TIMED tidal diagnostic and GOLD composition observations at constant local times. The COSMIC-2 constellation allows one to obtain the ionospheric tidal wave spectrum every day, e.g., using the hourly GIS data product, the radio occultation and in-situ observations. As such, we will be able to



directly connect driving and response from the data. By nudging the observed E-region wind fields with/without MJO into TIEGCM, the model will be used to diagnose the propagation of MJO signals into the IT parameters such as vertical ion drifts and plasma density. Running SD-WACCMX with the MJO removed in the nudged MERRA-2 data will allow one to investigate the coupling mechanisms from the troposphere into the ionosphere through term analysis. Our study will also shed light into the physical coupling of the MJO into the high latitude ionosphere, to explain a surprisingly large MJO signal that we identified in a preliminary analysis of PFISR electron density observations.

The proposal directly addresses FST #1 as it will quantitatively connect an important and recurring tropospheric weather phenomenon with its impact on the IT system using new satellite data sets, ground-based data, and state-of-the-art models. All data are publicly available through the NASA SPDF, the COSMIC-2 data repositories, and the CEDAR Madrigal database.

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**Fabrizio Sassi/Naval Research Lab****A link between weather regimes: Large-scale teleconnections in the Earth's atmosphere and ionosphere**

The extension of numerical models to the upper atmosphere (UA; thermosphere & ionosphere) with the inclusion of electrodynamics have produced high-fidelity whole atmosphere (WA) descriptions of the terrestrial weather, from the ground to the exobase (~500 km). Such WA interactions are mediated by traveling planetary waves, solar and lunar tides, and gravity waves that interact with the ionized atmosphere above about 100 km, and affect the structure and variability of what is called geospace weather. Thus, a link between the weather regimes of the lower atmosphere (LA; atmosphere below 100 km) and the UA exists. However, a holistic approach that includes both theory (numerical models) and observations (data assimilation), much needed to understand this connection, has been rarely implemented.

Forecasting the UA remains well behind predictive systems of the LA, due in part to compelling questions that remain unanswered: (a) what are the limitations due to forecasting errors; (b) what is the role of composition and transport to define the complex interactions between neutral dynamics and electrodynamics in the low latitude E-region; and, (c) can predictions in the UA benefit from a greater integration of modeling and observations with data assimilation techniques.

Our program focuses on large-scale interactions between the atmosphere and the ionosphere. The proposed research is articulated over four science objectives:

- a. Does the seasonally changing large-scale energy propagation from the LA determine the day-to-day weather of the UA?
- b. Are model errors of large-scale structures quantifiable using ensemble analyses/forecasts?
- c. Are interactive composition and transport crucial to understand the large-scale low-latitude E-region electrodynamics?



d. Can the predictability of UA properties be evinced from initialized forecasts? We will utilize a climate model (the Whole Atmosphere Community Climate Model, eXtended - WACCMX) either integrated with a data assimilation system (Data Assimilation Research Testbed DART) that includes observations in the UA, or nudged by atmospheric specifications (MERRA2; Modern Era Retrospective analysis for Research and Applications, version 2) up to about 65 km. The neutral dynamics produced by WACCMX will drive an ionospheric model (SAMI3 - Sami is Another Model of the Ionosphere) whose simulations are used to illustrate the effects of the neutral atmosphere on ionospheric dynamics, and the role of inline chemistry and transport that define the electrodynamics in the critical E-region. Observations from NASA space-based platforms such as GOLD, ICON, TIMED/SABER, and TIMED/TIDI, along with ionosonde measurements that describe the state of ionosphere, will be used to inform a data assimilation system in the thermosphere and to evaluate the forecast quality produced in both the thermosphere and ionosphere.

Ultimately, the project goals are to determine the role of the LA in the formation of the day-to-day weather of the UA, and quantify the predictability of their properties utilizing state-of-the-art tools and technique that integrate observations and theory.

Relevance: The proposed research addresses compelling questions for FST#1 in the LWS call that pertain to whole atmosphere interactions and predictions. In addition, the proposed study is directly relevant to the Decadal Survey Key Science Goal 2, Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs."

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### **Philip Scherrer/Stanford University**

#### **Toward a Consensus for Multi-Sourced Photospheric Magnetic Field Cross-Calibrations**

Magnetic fields drive solar activity that ranges from long-term variability of the solar cycle to short-term eruptions of flares and CMEs. Consistent magnetic field measurements over the solar surface is the first step toward establishing reliable magnetic configuration and connectivity in the heliosphere enabling better understanding and prediction of solar activity.

Full-disk, line-of-sight (LOS) photospheric magnetic field has been measured for many years at various observatories, including MWO, GONG, KPVT, SOLIS, WSO, MDI, and HMI. While these measurements exhibit remarkable agreement in distribution and patterns of magnetic flux, appreciable difference has been found in their measured values. Difference in instruments, calibration, and data processing contributes to this. To produce magnetic field data over the entire solar surface, several issues also need to be addressed. Those include (1) polar field that is poorly observed, (2) magnetic field in the far-side where direct observation is not available to date and technology to infer magnetic flux remains to be made robust, and (3) deriving consistent radial field (Br) from LOS, or vector field. Accurate Br is the data many models of coronal and interplanetary fields use. Data from different observatories, together with different methods to deal with those



issues, has led to significant discrepancy in model results. This seriously influences efforts to advance knowledge in understanding solar activity and its impact. Thus achieving consensus of magnetic field over the Sun's surface is vital.

We propose three tasks: 1) To seek a consensus for those magnetic field measurement cross-calibrations; 2) To derive synoptic maps of Br by addressing issues of polar field, use of far-side inferred flux, and conversion from vector and LOS data; and 3) To investigate the implied open flux problem by using our consensus field data in the photosphere.

We propose to employ a comprehensive methodology for this investigation. For task 1, we will use existing methods to examine the saturation correction, center-to-limb dependence of measurement, and spatial resolution of the data.

We will employ NSO's simulators of GONG and HMI extended to other instruments to validate and understand instrument differences. These will help develop cross-calibration between data from MWO, WSO, KPVT, GONG, MDI, SOLIS, and HMI.

For task 2, we will test existing schemes and develop new methods to correct polar field estimates. We will use observations and surface flux transport models to evaluate the methods. If it becomes available, we will also use SO/PHI to improve validation. We will examine impact of newly-emerging active regions on the far-side to the modelings by use of our recent O2R project that maps the far-side magnetic flux from helioseismic data. We will incorporate full-disk vector magnetograms from SOLIS and HMI to improve current model-dependent synoptic maps of Br. We will evaluate our final true synoptic (aka synchronic) maps by applying various models to the data and by comparing model results with observation.

For task 3, we will employ heliospheric models using final synoptic maps of Br and examine the modeled open flux with in-situ observations.

The proposed work cross-calibrates full-disk magnetograms taken by various observatories, provides consensus photospheric magnetic field over the Sun's disk, and produces reasonably reliable synoptic maps of Br. This work is relevant to the science goal from the Heliophysics Decadal Survey: to "Determine the origins of the Sun's activity and predict the variations in the space environment". This is directly relevant to the objectives of the Focused Science Topic 4, "Towards a Quantitative Description of the Magnetic Origins of the Corona and Inner Heliosphere." The resulting data will be available to the other members of the LWS/FST as well as the world at large.

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**Peter Schuck/NASA Goddard Space Flight Center**  
**The Origin of the Photospheric Magnetic Field: Mapping Currents in the Chromosphere and Corona**

Science Goals and Objectives: Our science goal is to quantitatively determine the origin of photospheric magnetic fields. In particular, our goal is to distinguish between fields produced by currents in the solar atmosphere and the solar convection zone and to use this information to determine the magnetic origins of the corona and inner heliosphere. The photospheric magnetic field forms both the theoretical and observational foundation for understanding the structure, evolution, and eruptive potential of the solar atmosphere. Indeed, the magnetic field at the solar photosphere is a crucial input to both empirical and physics-based models of the corona and solar wind." Our objectives are to use this determination of the origin of photospheric magnetic fields to address the following fundamental science questions:

1. What is the origin of the photospheric field?
2. What is the non-potential state of the solar corona? Do active regions emerge with current? How common are partially dressed currents in the solar atmosphere?
3. How does the photosphere generate coronal non-potentiality?

Methodology: The PI has developed a sophisticated tool CICC for distinguishing the coronal and chromospheric contribution to the photospheric magnetic field from the convection zone contribution with vector magnetograms. Preliminary work has demonstrated that a measurable fraction of the photospheric field in active regions is produced by current systems above the photosphere in the chromosphere and corona. This tool will be applied to a statistically significant sample of full-disk SDO/HMI vector magnetograms and a representative sample of Carrington maps and Hinode vector magnetograms to produce CICC magnetic maps, with rigorous uncertainties, of the fingerprints of chromospheric and coronal non-potentiality in the photosphere. These tools will also be applied to simulations of both boundary driven energization of the corona and of dynamic flux emergence from the convection zone to the corona, for comparison with the results of the observational study.

Relevance to FST Science Objectives: This work directly addresses and impacts all three of the Focused Science Team objectives. (1) Understand how the magnetic field drives coronal and heliospheric structure and dynamics." Using CICC magnetograms we will quantify the detailed development of the fingerprints of coronal and convection zone currents in the photosphere to ultimately characterize coronal and heliospheric structure. (2) Understand how magnetic connectivity evolves from the photosphere to the inner heliosphere." Using the CICC radial fields we will determine the connectivity of the inner heliosphere with just the convection zone sources and compare this against traditional results using the total radial magnetic field. (3) Understand how plasma processes or time-dependent evolution lead to global non-potentiality." Using the CICC decomposition we will determine the photospheric signature of chromospheric/coronal



non-potentiality in both full-disk vector magnetogram observations and in a suite of flux-shearing, -cancelling, and -emerging simulations.

Potential Contributions to Team Effort: The evolution of the radial field produced by the convection zone determined by our CICCI analysis will prove useful to the FST team for modeling global solar and heliospheric phenomena such as surface flux-transport, fast versus slow solar wind acceleration, the structure of the global solar magnetic field, and the location of the heliospheric current sheet. Similarly, any boundary driven simulations of the corona or solar wind will benefit from the insight provided by CICCI analysis of the driven boundary. For global-scale modeling CICCI can provide the convection zone field in the photosphere which may be a better boundary condition for the heliosphere than the total field that conflates the convection zone and coronal current sources.

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**Yi-Ming Wang/Naval Research Lab**  
**Constraining Solar Magnetograph Measurements Using the Observed**  
**Interplanetary Field and EUV and White-Light Coronal Images**

Background

Reliable measurements of the photospheric magnetic field are essential both for a better physical understanding of the solar corona and for improved space weather predictions. Uncertainties in these measurements make it difficult to predict accurately the occurrence of high-speed wind streams and CMEs at Earth. Extrapolations of magnetograph measurements generally underestimate the interplanetary magnetic field (IMF) strength by factors of 2--4. In addition, we have recently shown that magnetograms underestimate the amount of minority-polarity flux inside active region plages and coronal holes, raising the possibility that ephemeral regions (ERs) may be a major contributor to coronal and solar wind heating.

Objectives

Our objectives are: (1) To understand why extrapolations of photospheric field maps tend to greatly underestimate the radial IMF strength (the "open flux problem"), focusing on the possible roles of Zeeman saturation, line weakening, zero-point calibration errors, open flux outside dark coronal hole areas, and transients/CMEs. (2) To develop procedures for modifying the magnetic synoptic maps so as to improve the agreement with the observed EUV and white-light coronal structures, as well as with in situ measurements of IMF structure and solar wind variations. (3) To determine whether the rate of ER emergence inside active regions and coronal holes is sufficient to provide a major or even the dominant contribution to coronal heating.



## Methodology

(1) Using correlation analysis, we will compare the open fluxes, dipole strengths, and total fluxes derived from MWO, WSO, KPVT/SPM, SOLIS, GONG, MDI, HMI, and SPOT synoptic maps with each other, and the open fluxes with the observed radial IMF strength (from OMNIWeb, PSP/FIELDS, and SO/MAG). Agreement between the total fluxes measured by different observatories does not imply that their dipole strengths and open fluxes are in agreement, and a major source of the open flux problem may be errors in the dipole strengths. An important new idea to be examined is that the measured field strengths depend sensitively on where the magnetographs sample the line profiles. The contribution of CMEs will be estimated using the Richardson--Cane ICME catalog. (2) We will apply PFSS and PFCS extrapolations to the photospheric field maps to derive the configuration of coronal holes and streamers and compare the results with AIA, EUV, LASCO, SECCHI, WISPR, SoloHI, and Metis observations. The magnetic maps will be adjusted so as to improve agreement with the coronal, IMF, and solar wind observations, e.g. by adding or subtracting flux from the polar regions. This procedure will allow us to investigate systematic sources of error in the magnetograms and their dependence on the phase of the solar cycle. (3) Using AIA and EUV images taken in different EUV passbands, we will compare the looplike fine structure inside unipolar network and plages with that in quiet regions, to test the hypothesis that the rate of ER emergence is the same over the entire solar surface and independent of solar cycle phase.

## Relevance to FST #4 Objectives and Potential Contributions to the Team

The objectives of this proposal are relevant to two of the main FST #4 objectives: "Understand how magnetic connectivity evolves from the photosphere to the inner heliosphere" and "Understand how the magnetic field drives coronal and heliospheric structure and dynamics." Measures of success are the same as those suggested in B.5, Sect. 5.2 ("Improved modeling of the solar corona....") Our basic objective is to improve space weather predictions by identifying the main sources of error in magnetic synoptic maps.

The PI and Co-I will contribute more than 35 years' experience in using photospheric field measurements to understand better the physics of coronal holes, coronal streamers, IMF variations, and solar wind streams.

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## **Chih-Ping Wang/University of California, Los Angeles** **Understanding warm plasma cloak in the magnetosphere**

Science goals and objectives:

The warm plasma cloak (ions of a few eV to hundreds of eV and bidirectional field-aligned) is one of the two major cold magnetospheric populations (the other one being cold plasmasphere) and it plays important roles in several key magnetospheric processes. There is an important aspect of plasma cloak ions that is missing from the previous



observational and simulation studies. It is quite often to observe large enhancements (up to a factor of 10) in the cold field-aligned ion fluxes (cloak ions and outflow ions) on a time scale of a few minutes to tens of minutes with a spatial extent of a few RE, and the enhancement can exhibit an energy-dispersion feature. This mesoscale enhancement shows a dynamic aspect of the formation of the cloak ions that have not been explored and understood. Therefore, the overarching science goal of this study is to establish a better understanding of the strong mesoscale enhancements of the plasma cloak ions from observations and to investigate the responsible physical processes with global kinetic simulations. Our two objectives are: (1) Objective 1. Establish observational understanding of mesoscale enhancements of plasma cloak ions using THEMIS data. (2) Objective 2. Establish physical understanding of plasma cloak mesoscale enhancements using 3D global hybrid simulations.

Methodology:

Observation data: We will use satellite data from THEMIS (2007 to 2020) to investigate plasma cloak ions and outflow ions.

Observation Tasks: (1) Investigate each mesoscale enhancement of field-aligned cold ions observed by THEMIS and characterize its temporal variation (field-aligned type and energy-dispersion types), spatial extent, and the corresponding plasma sheet conditions. (2) Statistically determine the mesoscale enhancements of field-aligned cold ions according to their characteristics in energy-dispersion, field-aligned type, spatial extent, their dependences on MLT sectors and the plasma sheet conditions.

Simulation: We will use the 3D global hybrid code (ANGIE3D) developed at Auburn University to self-consistently simulate ion kinetic processes for the formation of H<sup>+</sup>, He<sup>+</sup>, and O<sup>+</sup> plasma cloak in a realistic and dynamic magnetosphere. ANGIE3D has been used to study the ion dynamics within the Earth's magnetosphere.

Simulation Tasks: The proposed simulation runs will be conducted in two different ways: (1) Artificially specify and control the outflow ions. We will run simulations with factors controlling the ionospheric sources. And we will run simulations with steady and disturbed plasma sheet conditions. (2) Using empirical outflow models driven self-consistently by the simulated magnetosphere. We will conduct two simulation runs, one with steady and one with disturbed plasma sheet, using the empirical outflow driven self-consistently.

We will conduct observation-simulation comparisons to determine which physical processes can contribute to the observed mesoscale enhancements of cloak ions.

Relevance: Our proposed study of the plasma cloak is directly relevant to the Focused Science Topic (FST) #2 Pathways of Cold Plasma through the Magnetosphere". Our goal is directly relevant to the goal of FST #2 make significant progress towards understanding and predicting the complex feedback between ionosphere outflows and magnetospheric plasma". Our two objectives are relevant to the objectives of FST #2 Provide a better understanding of the origin of the warm plasma cloak; and to understand the factors controlling these sources." Our results can contribute to the Science Team's effort to improve the characterization of cold plasma composition and distributions" and advance the self-consistent modeling of cold plasma processes and processes controlled by the cold plasma" Our study directly addresses a goal from Heliophysics Decadal Survey, Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere".



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**Liang Zhao/University Of Michigan, Ann Arbor**  
**Global Evolution of Solar Wind along Solar Cycles**

**Science Goals and Objectives**

The variation of the Sun and the solar wind influence every aspect of the Heliosphere. Since the unusual solar minimum between cycle 23 and 24, the weakened solar activity level has been directly influencing the solar wind properties and the interplanetary magnetic field. How the Sun's weakening activity level affects the large-scale evolution of the solar wind throughout the heliosphere becomes a more crucial question than ever. To answer this question, we propose a 4-year research project to investigate the variation of the solar wind and the interplanetary magnetic field in responding to the changing solar cycle. This proposed project will directly address one of the 2021 LWS Focused Science Topics (FSTs): Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle". Particularly, we will focus on the following scientific goals:

- 1) To understand the impact of the changing solar cycle on the long-term and large-scale evolution of solar-wind structures ;
- 2) To understand the impact of the changing solar cycle on the topology of the solar coronal magnetic field and the Heliospheric Current Sheet (HCS).

**Data and Methodology**

We will perform three different types of investigations, including data analysis, numerical modeling and Machine Learning (ML) / Artificial Intelligence (AI) prediction. Specifically, we will use solar wind and magnetic field data from instruments across the Heliophysics System Observatory (HSO): ACE, Wind, STEREO, SOHO, Hinode, Parker Solar Probe (PSP), and the observations of the joint ESA-NASA missions, Ulysses and Solar Orbiter (SO). We will utilize the Potential Field Source Surface (PFSS) model and the Current Sheet Source Surface (CSSS) model to track the coronal magnetic field from the Sun to the Earth. In addition, ML/AI techniques will be applied to the data to more objectively categorize the solar wind types and to predict the future behaviors of the Sun's magnetic field topology. In details, we will:

- 1) Utilize the long-term solar wind measurements to quantify how the solar-wind properties change responding to the changing solar cycle. Solar wind plasma in-situ properties will be examined and compared across different phases of solar cycles. We will use coronal EUV images to examine the evolution of the corona.
- 2) Apply ML/AI data analysis techniques to solar wind data to classify the wind types.
- 2) Connect the in-situ measurements of the long-term solar wind to the Sun by using PFSS and CSSS models, to explore the wind's coronal sources. We will examine the coronal origins of the solar wind with S-web (Q-map) calculated by PFSS, to investigate whether the winds are HCS/helmet streamer or pseudostreamer-associated.



3) Use the Sun's source surface synoptic maps (calculated by the PFSS) to examine the evolution of the HCS topology. We will investigate how the changes of HCS topology affect the solar wind structure. We will apply AI/ML techniques to predict the topology of the HCS, so that to predict solar wind structure.

Relevance and Contributions to the Focus Team Effort:

Our proposed work is directly related to one of the FSTs, Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle. The outcomes of our project will provide: 1) a full picture of how the solar wind structure evolves in a large-scale in the recent three solar cycles. 2) A new view of how the HCS controls the equatorial solar wind in the heliosphere in a long-term. And 3) a new insight of how the changes of the solar corona affect the solar wind that engulfs the whole Heliosphere. The achievement of our science goals will be the key milestones in addressing this FST.

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