Heliophysics Living With a Star (H-LWS) Program
Abstracts of Selected Proposals
(NNH17ZDA001N-LWS)

Below are the abstracts of proposals selected for funding for the LWS program. Principal Investigator (PI) name, institution, and proposal title are also included. One hundred and seventeen proposals were received in response to this opportunity. On October 17, 2018, 30 proposals were selected for funding.

Spiro Antiochos/NASA Goddard Space Flight Center
The Role of Magnetic Reconnection in the Onset of Solar Eruptions

Objectives: NASA space-based missions have revealed that magnetic reconnection is the dominant process for explosive energy release from the Sun to the magnetosphere and throughout the heliosphere. Reconnection is well known to be the driver of the largest explosions in the solar system, giant eruptive solar flares. Observations and theory have suggested that reconnection is also the critical process underlying the energy buildup leading to CMEs/eruptive flares, and may well be responsible for eruption onset, but this hypothesis needs definitive testing. We propose a research program designed to attack this fundamental question in Heliophysics: What is the role of magnetic reconnection in the onset of major solar eruptions? Answering this question is critical for achieving the Focused Science Topic (FST) objective of "Understanding the Onset of Major Solar Eruptions" and for achieving NASA's goals of understanding the Sun and solar system.

Methodology: The proposed work builds on our extensive studies of magnetic reconnection as the initiation mechanism and the driver for solar eruptions ranging from small coronal-hole jets to large active-region CMEs/eruptive flares. The proposed research also builds on our pioneering theoretical and numerical studies of how magnetic reconnection leads to the free-energy buildup required for explosive eruption. The work consists of a balance of theoretical and numerical studies using our 3D adaptively refined MHD solver (ARMS), which is uniquely powerful for simulating magnetic reconnection in the solar corona. We will employ the methodology that we have used to attack successfully many fundamental Heliophysics problems: first develop insight by investigating idealized models that isolate the key physics of the problem, then apply the understanding gained to calculate predictive signatures that can be tested with observations from NASA missions and incorporated into space-weather models.

Proposed Contribution to the FST Team Effort: We will contribute to the FST Team our unique physical insight and understanding of solar eruptions as demonstrated by our pioneering theoretical models, such as breakout, that are widely used by the world-wide Heliophysics community for interpreting observations. We will also contribute our numerical technology, ARMS, that has been developed over the past two decades exactly for the problem of reconnection-driven coronal activity. We will make definitive calculations of reconnection-driven eruption for comparison with observations and with other onset mechanisms. Our proposed research program is essential for understanding the fundamental processes leading to solar eruptions. We look forward to working with the observational groups and with the other modelers in the FST to develop a definitive understanding of eruption onset and useful predictive signatures.

The Principal Investigator directing this project is Dr. Spiro K. Antiochos of NASA/GSFC. Dr. Antiochos is a world-recognized expert in both theories and observations of solar eruptions. He will be assisted by Drs. C. Richard DeVore and Judith T. Karpen from GSFC, Joel T. Dahlin from the University of Maryland, and Peter F. Wyper from Durham University.

Graham Barnes/NorthWest Research Associates, Inc
The Role of Magnetic Topology in Determining the Eruptivity of Solar Flares

Science Objectives

The geometry, connectivity, and topology of the large-scale coronal magnetic field play a key role in determining whether a solar reconnection event will result in an eruption, either by influencing the location where magnetic reconnection releases energy for an event, or by determining the pathways and access to open field that allow an eruption to proceed. The research proposed here involves studying a large sample of flaring active regions to determine which topological features are most closely associated with both eruptive and non-eruptive events.

Knowledge of topological features that affect the eruptivity of active regions will provide insight into their cause, either in the context of the type of reconnection generating the event (e.g., whether coronal null points are most strongly associated with eruptions, as in the breakout model), or in the context of understanding why some flares lead to eruptions but others don't (e.g., whether access to open magnetic flux facilitates or enhances the chances of an eruption). By determining how often bald patches exist, the question of whether a flux rope must be present prior to an eruption, or if it can form during the eruption, will be addressed. Estimating the rate at which eruptions occur with and without particular topological features will yield probabilistic forecasts of whether the conditions are favorable for an eruption, should a flare occur. Of particular interest would be a topological feature associated with very low eruption rates, as this can be used to improve the ability to issue all-clear forecasts.

Methodology

The large-scale coronal topology will be determined in two different types of models: the oft-used Potential Field Source Surface (PFSS) model and a magnetofrictional (MF) model. Line-of-sight magnetograms are available for the PFSS models over the past two sunspot cycles from both SDO/HMI and SoHO/MDI, while for a shorter interval, SDO/HMI additionally provides vector magnetograms that will be used to drive the MF model and determine the presence of bald patches. The topology of the modeled coronal magnetic fields will be determined immediately prior to a large number of (eruptive and non-eruptive) solar flares. Topological and geometrical features of interest include the locations of null points in the coronal volume, positioning and orientation of separatrix surfaces, and the locations of domains of open fields relative to the active region cores. The importance of each feature in determining the eruption rate will be assessed by computing the Bayes factor of competing models: one for which the rate is the same with and without a given topological feature, and another for which the rate changes depending on the presence of the topological feature.

A significant part of the proposed effort will go into determining how robust the model topology is. Since the random error in vector field measurements is unlikely to be the dominant source of uncertainty in these models, we will focus on two other aspects: (1) how persistent are particular topologies given the continual evolving surface magnetic fields, and (2) how sensitive are the topological features to the particular coronal field employed. In the first case, the focus will be on determining the lifetime of topological features. In the second case, we will characterize the similarity or difference in the topologies provided by the PFSS and MF models.

Contributions to the Focused Science Team Effort

The proposed investigation will provide guidance for more realistic modeling efforts by determining what coronal topology should be included in models for eruptive events. It can also be combined with a flare forecasting algorithm to immediately produce probabilistic forecasts of eruptive events. If the presence or absence of a particular topological feature is strongly associated with no eruptions, this could lead to a more robust determination of all-clear periods.

Natalia Buzulukova/University of Maryland, College Park
Quantifying solar wind-magnetosphere-ionosphere response to extreme driving conditions

The proposal will seek to understand and quantify the solar wind-magnetosphere-ionosphere response for extreme driving conditions using the 3D multifluid MHD code (BATS-R-US) coupled to the inner magnetosphere module (CIMI), the module of ionospheric electrodynamics and the outflow module. Historical data available for extreme geomagnetic storms will be compared with the simulations when available.
Scientific objectives:
A few scientific topics are selected for detailed analysis, including the response of the coupled magnetosphere-ionosphere system to Carrington-type events, paying attention to the role of ring current population, and the role of ionospheric effects, and the role of solar wind drivers. The proposal will study physical mechanisms that could explain unusually fast recovery rate for the Carrington event. These processes include elevated O+ outflow and faster rate of charge-exchange losses, ionospheric effects, magnetopause losses, wave-particle interactions. In relation to the applications of space weather, we will

also examine the response of electrons in the energy range 5-50 keV in the inner magnetosphere and along GEO orbit. The response of the electron fluxes will be studied as a function of the strength of the storms, in order to find optimal conditions for formation of intense electron fluxes.

Methodology:

To achieve scientific objectives, we will model the global coupled system for some extreme historical geomagnetic storms, including the Carrington event. The modelling tools will include the coupled MHD-ring current code (CIMI-BATS-R-US) and the standalone version of CIMI model. As a reference, a few moderate/big storms (with |Dst| ~ 200-300 nT) will be considered, and the output of the model will be compared to that of modern data sets from Geospace fleet. We will quantify the similarities/differences between the model and the response observed in Dst/SYMH indices, particle fluxes and magnetic fields (if available). Quantifying the differences between observations and the model results for moderate/big storms will help to understand and predict the differences between the model and the actual magnetosphere for extreme conditions, as well as will allow to estimate model errors and limitations.

Importance of the proposed work:

The proposed work will provide a better description of extreme geomagnetic storms, including Carrington type events, and fill some critical gaps in the current understanding of extreme activity. We will address the fast recovery rate observed for the Carrington event, exploring different proposed physical processes, and simulate these processes with the state of the art global models of magnetosphere/ionosphere. Electron fluxes in the 5-50 keV energy range are responsible for surface charge/discharge phenomena. It is important to understand that current results show the existence of some optimal level of activity in order to form the most intense electron fluxes. Quantifying the response of electron population to different geomagnetic storms will help to develop mitigation strategies for the worst-case scenarios. The expected outcome will also allow more accurate modelling representation of extreme geomagnetic storms and help to understand key processes that occur during such events.

Peter Chi/University of California, Los Angeles

M-I Coupling Effects on Ion Circulation in the Inner Magnetosphere

This investigation focuses on the M-I coupling effects on the ion population in the inner magnetosphere, addressing one of the essential elements of the LWS Focused Science Topic "Ion Circulation and Effects on the Magnetosphere and Magnetosphere-Ionosphere Coupling." Through data analysis and model calculations, we answer the following three outstanding science questions (SQ) on the density structures in the inner magnetosphere, including the oxygen torus, the warm plasma cloak, and the plasmaspheric plume:

SQ1. Is the oxygen torus distinct from the warm plasma cloak? Are these thermal or non-thermal plasma populations?

SQ2. What are the consequences of ring-current-associated electron heating? Are the resulting ion populations consistent with observations of the oxygen torus or warm plasma cloak?
SQ3. What is the typical mass density of the plume? Are observed plumes consistent with current first-principles simulations? Do the simulations require new physics?

We examine both spacecraft measurements and numerical model results to address the three posed science questions regarding the ion circulation in the inner magnetosphere. The major sources of spacecraft data come from the measurements by the Van Allen Probes and Magnetospheric Multiscale (MMS). Specifically, HOPE and HPCA instruments provide the measurements of warm ions. The charge density is inferred from the measured upper hybrid resonance frequency, and the mass density of the bulk plasma is inferred from the field line resonance frequencies observed by electric and magnetic field instruments. The comparison between mass and charge densities can estimate the ion composition in the bulk plasma. Numerical modeling based on the SAMI3 model with the optional ring current module is performed to investigate the ring current heating effect on O+.

The proposed research addresses longstanding questions about the nature of the torus, cloak, and plume plasmas. This is a necessary step for understanding the response of the inner magnetosphere to storms. This work will impact the development of space weather models, especially models of storm-time phenomena. Predictions of radiation belt growth and decay, of storm-time convection, and of ionosphere electron density gradients will be affected by this work.

The proposed research directly addresses some objectives of the LWS Focused Science Topic "Ion Circulation and Effects on the Magnetosphere and Magnetosphere-Ionosphere Coupling." It is also relevant to the Heliophysics Decadal Survey goal to "determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." The proposed investigation can provide data and model results of ion density and temperature that can assist other investigations in the Focused Science Team.

Christina Cohen/California Institute of Technology
New Insights into SEP Sources, Acceleration, and Propagation: An Integrated Observation-Modeling Approach

Science Goals: Solar energetic particle (SEP) events can be a significant hazard to humans and technological infrastructure in space; predicting their intensity, location, and impacts is an imperative. Despite years of study, true predictive capabilities for SEP events continue to be hampered by open fundamental questions regarding their genesis close to onset from low in the corona, and how they populate the heliosphere. Studies combining the observations of SEPs near Earth (using, e.g., ACE, SOHO, and GOES) with those from the twin STEREO spacecraft have revealed longitudinal distributions that defy our general understanding of energetic particle transport, and point to the importance of magnetic field structure, coronal mass ejection injection and structure. Events such as 3 November 2011 indicate that SEPs can fill the inner heliosphere in ~30 minutes, much faster than expected. Statistical surveys of multi-spacecraft events show that the longitudinal distributions of SEPs vary substantially from event to event and the characteristics are, surprisingly, not clearly organized by rigidity but do depend on energy. Interpreting these observations requires an integrated approach that combines state-of-the-art analysis of SEP, solar, and interplanetary measurements with cutting-edge simulations starting from the Sun and extending through the low corona and inner heliosphere. By studying both individual events as well as general characteristics determined from survey studies, we will investigate key questions, including the role of coronal mass ejections (CMEs) and low-coronal shock formation in the acceleration of SEPs, the effect of field line connectivity on SEP transport, and the mechanisms that influence various SEP characteristics observed at 1 AU, such as rise time, longitudinal spreading, and compositional variation.

Methodology: Our proposed work leverages a new simulation tool that couples realistic, three-dimensional (3D) magnetohydrodynamic (MHD) simulations of CME events with 3D solutions of the focused transport equation. Versions of this new tool (SPE Threat Assessment Tool, or STAT) will have been delivered to the CCMC by the start of the proposed work; the tool combines the Predictive Science CORHEL (Corona-Heliosphere) MHD modeling suite with the University of New Hampshire Earth-Moon-Mars Radiation Environment Module (EMMREM) and can provide particle flux, fluence, and dose-rate predictions for different points in the heliosphere. We will perform detailed flare/CME event simulations for events carefully selected from recently catalogued SEP events observed by STEREO, ACE, and GOES to elucidate the underlying source locations and mechanisms of SEP acceleration/transport as well as test and improve the models. The models will be used to gain new insights into the recent observation of a general energy dependence of SEP longitudinal distributions (and lack of rigidity dependence) and investigate the influence of the shock/compression properties, its surrounding environment, and the conditions of the inner heliosphere on the characteristics of the SEP event observed at 1 AU. These models will significantly aid the interpretation of Parker Solar Probe observations when they become available and connect them to 1 AU observations.

Proposed Contributions to the Focused Team Effort: As part of a larger systems approach to understanding SEPs, we will work with other selected teams to study events through modeling and observational analysis. We will provide simulation and data analysis results as well as useful visualizations to the whole FST team. We will provide our expertise in modeling and SEP analysis to other team members and will capitalize on the additional expertise, particularly in the analysis of solar and solar wind observations, that other members will bring to the team effort.

Anthea Coster/Massachusetts Institute of Technology
Ionospheric Response to Super Storms and Its Role in Geospace Coupling

Geomagnetic storms produce significant changes in the ionosphere. The equatorial ionization anomaly (EIA) becomes enhanced, with its crests moving poleward and its peaks becoming larger. In the mid-latitudes, typically following a significant uplift in the height of the F-layer, a large increase in the electron density is observed. A plume of storm enhanced density (SED) can form with its base in the mid-latitudes and can extend into the polar region. Associated with this plume are sharp gradients in the electron density that can cause scintillation and degradation of radio signals. These ionospheric storm time features are encompassed by what is known as the positive storm phase. Several hours after storm commencement, associated with changes in thermospheric composition and neutral winds, a prolonged depletion of the ionospheric electron density, known as the negative storm phase, is observed. This phase can last from a few hours to a few days. Storm-time electric fields play significant roles in producing these effects, and they can be generated by the disturbance wind dynamo and/or by the magnetospherically-imposed electric fields such as the penetration electric field or the sub-auroral polarization stream (SAPS). Which mechanism plays the dominant role is not well understood and may depend on the size of the geomagnetic storm in addition to season, time of storm onset, and solar activity. How these typical storm-time features are modified during superstorms is the key question that this proposal will address.

Our goal is to illuminate the role of these mechanisms during ionospheric superstorms and to better understand the coupling between the magnetosphere and ionosphere and between the thermosphere, ionosphere, and mesosphere. Using multipoint and multi-instrument observations during superstorms and other storms, we will explore: the development of SAPS and the associated SED feature; the formation of the equatorial super-fountain; the relationship of the thermosphere density and winds to strong SAPS; the launching of large scale traveling ionospheric disturbances (LSTIDs) from the polar regions; temperature and wind changes in the mesosphere-lower thermosphere region; and the length and duration of the ionosphere s recovery from superstorms. We will also evaluate the potentially huge deviation of the ionospheric parameters during superstorms from empirical data models.

The types of data that will be used for storm analysis include: 1) two-dimensional global electron content data that will be produced from ground-based and space-based GNSS receivers; 2) regional observations of the ionosphere by SuperDARN, Fabry-Perot interferometers, and incoherent scatter radars; and 3) in situ data by DMSP and TIMED/GUVI, and potentially by ICON and GOLD. MIT Haystack ground-based TEC maps are available from the year 2000 on. For selected storm periods, low earth orbiting (LEO) satellite data will be merged into our routine TEC data product. These data will be used to study a range of storm-time ionospheric features at equatorial, midlatitude, and high latitudes.

Our proposed contributions to the focus team effort will include providing multiple data sets, e.g. ISR data, DMSP data, TEC ground maps, LEO-TEC observations, FPI data, for superstorm (mostly in 2001-2004) and other major storm periods. The data can be used to verify simulation results and to examine the limits of state-of-the-art models for superstorm events. Model-data comparisons can also provide more insight into our physical understanding of superstorm features. In addition, our analysis of ionospheric superstorm effects will be brought to the team, and we will use the modeling capabilities of other team members to study the role of the ionosphere in geospace coupling. Of particular interest is the simulation of SED/TOI, the role of SAPS in shaping SED, and the influence of SAPS on the local and global thermosphere and ionosphere.

Seebany Datta-Barua/Illinois Institute Of Technology
A nighttime ionospheric localized enhancement (NILE) at mid-latitudes during extreme storms

Science: This effort will identify the extreme storm (Dst < -300 nT) dynamics that cause a co-rotating mid-latitude nighttime ionospheric localized density enhancement (NILE). During the extreme storms of solar cycle 23 a "hot spot" of 10 times as much total electron content (TEC) as the background nightside occurred within a span of only 500 km in the Gulf of Mexico region. The magnitude and localization of a NILE at mid-latitudes adversely affects the availability of GNSS-based augmentation systems providing single-frequency user aircraft precision navigation service, e.g., the Wide Area Augmentation System (WAAS). No first principles ionospheric model predicts the existence of NILEs. Possible causes include an electrodynamic effect tied to the South Atlantic Anomaly or a super-fountain associated with interplanetary electric fields. This proposal will investigate events from solar cycles 23 and 24 to establish whether the phenomenon only occurs during extreme storms, determine whether such events are unique to the American sector, and test causal hypotheses by imaging the plasma density globally to estimate the drivers most consistent with the observations.

Method: The proposed work will combine advanced models with space-based data from NASA observatories along with ground-based measurements, all publicly available, to estimate the formation mechanism using the latest data assimilative techniques. The first principles model forming the a priori state will be SAMI3 (SAMI3 is Also a Model of the Ionosphere). Two data assimilative (DA) methods will subsequently ingest data to update the SAMI3 background: Ionospheric Data Assimilation 4-Dimensional (IDA4D) and Estimating Model Parameters from Ionospheric Reverse Engineering (EMPIRE). We will use SAMI3, IDA4D, and EMPIRE to understand the physical processes consistent with the existence of a localized mid-latitude persistent nighttime plasma enhancement. SAMI3 has global fidelity in producing storm enhanced density, a possible precursor to the NILE. IDA4D will update the SAMI3 background model of plasma density with ground- and space-based density data, including from COSMIC, to produce a global time-varying specification of plasma densities. EMPIRE will update background models of electric potential and neutral winds based on electron density from IDA4D and measurements of the drivers from TIMED, DMSP, and C/NOFS. With these data covering the last two solar maxima, we will examine both extreme and not extreme storms. Space-based data are key to assimilation for dynamic driver estimation. DA lets us address the science goals because, while models do not yet predict the NILE itself, observationally driven updates offer optimal updates to the models, giving insight into the physics distinguishing NILE conditions from null events.

FST Contributions: This proposal responds to Focused Science Topic 4: Understanding physical processes in the MITM system during extreme events. Global adjustments of first-principles electric potential based on observational stormtime conditions will indicate the states in which models most need adjustment during extreme storms. The study will help to show whether an extreme storm is a necessary condition for the NILE. This investigation will provide evidence of progress toward accurate simulation of extreme Space Weather events and their effects in the IT system by providing a rigorous uncertainty on the estimated state from DA. Output covariances and comparison to validation data provide metrics for determining the successful outcome of the research. We will contribute the electric field and neutral wind fields produced from SAMI3 and EMPIRE, and density specification from SAMI3 and IDA4D, to the FST. This effort will contribute insight into the low-to-mid-latitude electrodynamics during extreme storms, bringing a greater understanding of a phenomenon that has known consequences for the precision navigation availability of WAAS.

Maher Dayeh/Southwest Research Institute
Linking Energetic Storm Particles to their Upstream Physical Conditions and Shock Properties

Current Understanding: Enhancements of >0.1 MeV/nucleon ions near 1 AU in association with the passage of an interplanetary (IP) coronal mass ejection (ICME) are often referred to as energetic storm particle (ESP) events. The primary candidate of producing these enhancements is diffusive shock acceleration (DSA). ESPs can produce significant increases in the near-Earth particulate radiation and pose severe hazards to astronauts and hardware in space. Physical parameters thought to affect ESP production include IP shock properties (e.g., speed, strength, obliquity) and upstream conditions ahead of the propagating shock (e.g., turbulence, seed populations, SW and IMF conditions). While several observational studies and theories have attempted to link ESP production to these drivers, reliable prediction of ESP properties (e.g. intensities, spectra, abundances), including their event-to-event variability, has so far proven elusive, indicating an incomplete understanding of how ICME-driven IP shocks accelerate ESPs.

Goal and Science Questions: Our overarching goal is to identify the dominant upstream and shock parameters that influence ESP properties and lead to their event-to-event variability, thereby advancing current understanding of ICME-driven shock particle acceleration. We will also determine whether these drivers can be used to predict ESP properties at 1 AU. We will achieve this goal by answering the following three science questions:

Q1. What is the relationship between upstream conditions, ESP properties, and IP shock properties at 1 AU?

Q2. How do upstream conditions and IP shock properties affect ESP production and properties?

Q3. Can upstream conditions and IP shock properties be used to predict ESP properties at 1 AU?

Methodology: We use energetic H-Fe ion, plasma and magnetic field measurements from ACE, Wind, and STEREO-A&B during solar cycles 23 and 24. Using specific criteria, we will identify all shocks and ESP events measured at 1 AU. For each ESP and when available, we will derive a matrix of parameters describing the upstream conditions, IP shock, and ESP. Statistical and correlation studies will follow to pinpoint the dominant drivers that influence ESP properties (Q1). Once the Upstream-Shock-ESP linkage is determined, we will utilize the Particle Acceleration and Transport in the Inner Heliosphere (PATH) model to explore the influence of these dominant drivers on ESP properties. PATH model inputs, constrained by observations, will be varied systematically to isolate the influence of each potential driver on ESP intensities, spectra and abundances (Q2). Using the parameter matrix derived in Q1, we will utilize Machine Learning algorithms to determine if and how upstream and shock parameters can be used to predict ESP properties (Q3). The relationships uncovered in these analyses are expected to lead to a more complete understanding of ICME-driven particle acceleration at 1 AU.

Relevance to NASA and LWS: Our project responds directly to the second Focused Science Topic (FST) and to two LWS Program Science goals, as indicated in the special FST contributions elsewhere in this proposal. Results are also relevant to two science goals of the 2012 Solar and Space Physics Decadal Survey, and to a key strategic goal of NASA's Heliophysics Division, i.e., understand the Sun and its interactions with the Earth and the solar system, including space weather

Yuhong Fan/University Corporation For Atmospheric Research (UCAR)
Observationally guided simulations of coronal mass ejections (CMEs)

We propose to perform magnetohydrodynamic (MHD) simulations of coronal mass ejections (CMEs) in the corona using observations of the photospheric magnetic fields as input. The goal is to determine the coronal magnetic field evolution of the CME events from the quasi-static build-up to the dynamic eruption, and to ascertain the properties of the eruption, such as acceleration, speed, and direction through the lower solar corona into the solar wind. The validity of the simulated magnetic field evolution will be examined by comparing with coronal multi-wavelength observations of selected events observed by SDO/AIA, SOHO/LASCO, STEREO, and Mauna Loa Solar Observatory (MLSO). The main scientific questions we want to address are: (1) What are the observational signatures that are indicative of the build-up of a magnetic flux rope and readiness for eruption? (2) What are the conditions that lead to confined vs. ejective eruptions and what are the crucial factors that determine the acceleration, terminal speed and orientation of the magnetic field in the out-going CMEs? (3) What are the conditions that can lead to the development of homologous and cannibalistic CMEs, and how do their interactions affect the CME speed, shocks and magnetic field structures.

We will use the Magnetic Flux Eruption (MFE) MHD code (Fan 2012, 2016, 2017) to carry out the simulations of CME initiation in the large-scale corona driven by an imposed flux transport at the base of the corona. For the imposed flux transport, we will first experiment with prescribing the emergence of idealized twisted magnetic flux ropes whose properties are guided by the observed flux emergence patterns (e.g. Fan 2016), and then we will use the electric field directly inferred from time sequences of vector magnetograms from SDO/HMI (Kazachenko et al. 2014, 2015). The MFE code solves the semi-relativistic MHD equations in a spherical domain with the thermodynamics taking into account the essential non adiabatic effects of the corona and transition region, including an empirical coronal heating, optically thin radiative cooling, and field-aligned thermal conduction (Fan 2017). We will construct synthetic EUV and X-Ray images as well as coronagraph white light images from our simulations of the CME source regions and eruptions, and compare them with SDO/AIA, SOHO/LASCO, STEREO, and MLSO/KCor observations of the simulated events.

The proposed study will directly contribute to the goals of the Focused Science Team Effort on the Focused Science Topics of "Understanding the Onset of Major Solar Eruptions". Our project integrates numerical simulations with observational synthesis to interpret observations of CME events for both the build-up phase and the dynamic eruption phase. Our observationally guided MHD simulations to determine the realistic coronal magnetic field evolutions of the CME events will (1) improve our understanding of the conditions for the readiness for eruption and identify their observational signatures; (2) quantify the build-up of free magnetic energy and determine the coronal magnetic field evolution of CME source regions given photospheric magnetic field observations; (3) improve our ability to determine the velocity and magnetic field structure of the outgoing CMEs needed to improve space weather forecasts. Metrics and milestones for determining the successful progress and outcome of the research include refereed publications on results of simulations that provide physical understanding and interpretation of the observed signatures of the CME events. The ability for our observationally guided simulations to reproduce the observed eruptive behavior first qualitatively and then quantitatively (e.g. the speed, direction and morphology of the CMEs) will be the milestones and measure of success of our project.

Tim Fuller-Rowell/University Of Colorado, Boulder
Understanding the Thermosphere-Ionosphere Response to Extreme Solar Events

The objective of this proposal is to understand how the thermosphere-ionosphere system responds to an extreme space weather event, such as the Carrington storm of 1859 or the solar wind conditions experienced by STEREO-A when a CME struck the spacecraft on July 23rd, 2012. These solar wind conditions provide a reasonable scenario for a once in a 100-year extreme solar storm impacting Earth. By targeting extreme events, we will address the needs of the Space Weather Action Plan, and in addition improve our understanding of the how the physical system responds to events at the level of the Halloween (October, 2003) and Bastille (July, 2000) geomagnetic storms.
With the obvious lack of observations, the physical models cannot be used blindly, but the model simulations will have to be carefully interpreted to address the following fundamental science questions: 1) How does the ionospheric plasma redistribution respond to the combination of the overly expanded magnetospheric convection to mid-latitudes and the strong penetration electric field to low latitudes? 2) How does the thermospheric circulation and neutral composition respond to Joule heating expanded well into mid latitudes, rather than the typical location at higher latitudes during storms? 3) Does the disturbance dynamo still play a significant role given the magnitude and possible dominance of magnetospheric convection? 4) How severe is plasmasphere erosion in response to the polar cap boundary and plasma escape well into mid-latitudes? 5) Do both positive and negative phases both still have a significant contribution in the response of the ionospheric plasma density and total electron content? 6) What is the level of thermal expansion and increase of neutral, and plasma density, at high altitude contributing to satellite drag? 7) Does the auroral NO production and radiative cooling cause the upper atmosphere expansion to saturate?
We will use the newly developed and tested ionosphere-plasmasphere-electrodynamics (IPE) model, with self-consistent electrodynamics, to simulate the ionospheric response, and the well-tested thermospheric component of the coupled thermosphere-ionosphere-plasmasphere model (CTIPe) for the thermospheric expansion and neutral density response. The models will be driven by the estimated or simulated response to extreme solar wind drivers from either empirical magnetospheric convection models or from MHD model simulations.
This simulation study will contribute to the Proposed Contributions to the Focused Science Team Effort by providing state-of-the art models as powerful tools for the investigation. In addition, the personnel will provide understanding of the physical system. Since there are no observations of the response to a Carrington-level event, understanding the physical processes and interpreting the model simulations is the only

way we can be sure the extrapolation of the response of the physical system is likely to be realistic. The proposers also have close collaboration with the MHD magnetospheric modeling groups, such as the OpenGGCM and Michigan Geospace model, and we are able to leverage and reinforce our on-going interactions with these groups and contribute to simulations of the two-way interactions and feedbacks between the magnetosphere and thermosphere-ionosphere systems.
In addition, in this proposal we will address the impact of an extreme space weather event on operational systems, including: How do changes in ionospheric plasma density impact satellite communications and navigation? What are possible perigee height changes due to the likely neutral density enhancement, and what part of the catalog would be de-orbited? How would in-track orbit uncertainties grow, and what are potential impacts on collision avoidance? By quantifying the impact on operational system, we will enable operators, planners, and decision makers to make appropriate choices to implement mitigation strategies.

Dale Gary/New Jersey Institute Of Technology

Spatial Distribution of Flare-Accelerated Particles and Their Role as Seed Particles for SEPs

Solar Energetic Particle (SEP) events are known to be associated with Coronal Mass Ejections (CMEs), with the high-energy particles likely to be accelerated by CME-associated shock waves en route to Earth. However, current theories of shock acceleration do not allow acceleration directly from the thermal pool, but rather require the pre-existence of a population of non-thermal 'seed' particles. The fact that SEPs are well associated with large solar flares suggests that particles accelerated during the flare might provide such seed particles. However, most of our knowledge of flare-accelerated particles comes from hard X-rays, high-frequency microwaves, or indirect evidence such as heating by downward-directed particles. These emissions are heavily weighted to the high-density, high-magnetic-field, lower-altitude parts of the flaring region far from the CME front. Recently, a new data stream has become available, multi-frequency microwave imaging from the Expanded Owens Valley Solar Array (EOVSA), which can directly image and obtain particle energy diagnostics of the relatively low-density, low-magnetic field, high-altitude parts of the eruption, thus linking flare-accelerated particles with the larger eruption and CME. Here we propose to combine the EOVSA microwave imaging and diagnostics with observations from solar space missions, including RHESSI, SOHO, STEREO-A, SDO, Hinode, and IRIS, as well as ground-based observations from Big Bear Solar Observatory (BBSO) to further explore this linkage and improve our understanding of the origin of seed particles in relation to SEP events.
The science goals and objectives of the proposal are: (i) to obtain flare-accelerated particle diagnostics at high altitudes using microwave imaging spectroscopy of dozens of flares already observed by the new EOVSA; (ii) to use NASA spacecraft and ground-based data to dynamically relate these spatially-resolved diagnostics to both the lower atmosphere and the wider eruption and CME.

Methodology. We propose to use the new data stream from EOVSA, which provides a new capability to obtain multi-frequency (2.5-18 GHz) radio images at 1-s cadence, with spatial resolution about 3" at 18 GHz. The data provide never-before-available diagnostics of energetic particles and coronal magnetic fields throughout the region linking flares to the associated eruption and CME. We will also use BBSO, SDO and Hinode data of jointly observed events to determine (1) properties of magnetic reconnection rates calculated from ribbon separation, (2) magnetic free energy in the hosting active region (AR), (3) magnetic decay index and twist in ARs with identified flux ropes. Our collaborators at Kyung Hee University will provide 3D parameters of associated CMEs and properties of EUV waves, using tools they have developed. We will apply these techniques to SEP events associated with AR 12673, and to similar events without SEPs to identify the necessary and sufficient conditions for effective seeding in these events.
Proposed Contributions: This Targeted Investigation is relevant to the Focused Science Topic "Toward a systems approach to energetic particle acceleration and transport on the Sun and in the heliosphere," for which EOVSA's unique sensitivity to high-energy particles and their transport provides the missing link between the flare (and host AR) and the ensuing eruption and CME. An understanding of this link is essential to prediction of which events will be accompanied by SEP events. The proposal will contribute to the FST effort by (1) using our team's expertise in analyzing SDO/AIA/HMI data and deriving key data products as described above for magnetic properties of source ARs and flares, (2) using our team's expertise in analyzing microwave and hard X-ray data for direct imaging and diagnostics of emission from energetic particles over a large region, and (3) using our team's expertise in characterizing CMEs and EUV waves.

Jorg-Micha Jahn/Southwest Research Institute
Heavy Ions Inside Geostationary Orbit

Science Goals and Objectives. Singly charged oxygen plays multiple key roles in magnetospheric dynamics. However, our quantitative knowledge of the multispecies ion dynamics inside geostationary orbit is still limited by sparse measurements. We create an empirical model of the inner magnetosphere multispecies ion plasma based on Van Allen Probes data (2012-present), and use this model to address science questions on the distribution and role of O+.

Project Objective: Develop a comprehensive empirical model of the inner magnetosphere near-equatorial multispecies ion environment and use the model to address Focus Science Team (FST) science.

Science Question 1: What is the spatial and temporal relationship between different O+ populations co-located in the inner magnetosphere, and what controls the distribution, amount, and characteristics of O+ during solar cycle changes?

Science Question 2: What is the role of lower energy (< 40 keV) hot O+ ions in the storm-time ring current?

Methodology. Key data sources for the model are Van Allen Probes data since its launch in late 2012: HOPE (ion data 1 eV through 50 keV), RBSPICE (> 150keV for O+), EFW (spacecraft potential; total plasma density; DC electric field), EMFISIS (total plasma density; magnetic field), OMNI solar wind data (solar wind context), and standard geomagnetic activity indices (e.g., sym-H, AE, etc.). The model is centered around an extensible relational database of binned data with sophisticated query and analysis capabilities.

The model describes species-resolved (O+, He+, H+) ion characteristics (spectra, PADs, moments) and environment parameters (e.g., total density, DC fields) as a function of solar wind and magnetospheric parameters on a configurable 2D L/MLT grid. Time information and data source coordinates are retained. Physical boundaries (e.g., plasmapause) and statistical uncertainties of all model outputs are provided. Outputs are validated with other data-driven models, where available.

Science questions are answered by creating model outputs driven by relevant input parameters and fiducial marks, followed by further analysis.

SQ-1: We perform statistical analyses of the distribution of various ion plasma populations and their drivers. The plasmapause mostly separates warm from cold plasma, therefore we study populations referenced to the plasmapause location. We compare statistical results to HEIDI kinetic model calculations of the ion dynamics inside geostationary orbit.

SQ-2: We perform statistical analyses on ensembles of storms, followed by a detail comparison between model outputs and HEIDI model calculations. HEIDI is seeded by pre-storm model outputs. We investigate the global role of below 40 keV O+ on ring current decay with HEIDI calculations, comparing with Van Allen Probes observations.

Proposed Contribution to the Focus Team Effort. This proposal contributes significantly to the ion circulation FST. As per the NRA: "Proposals to this FST should aim to determine heavy ion characteristics in the magnetosphere across a wide range of L-shells/geomagnetic latitudes (...)" providing "identification of what controls heavy ion characteristics in the ionosphere and magnetosphere; (...)". Specific investigations, e.g., "data analysis that seeks to characterize the spatial and temporal distribution of O+ in the inner magnetosphere (...)" are suggested.

We characterize the heavy (and light) ion environment for populations inside geostationary orbit in a comprehensive and flexible way using 5+ years of Van Allen Probes data. Our model and science analyses are performed in collaboration with the FST. The model and its outputs are available to the FST during the project. We can expand/modify the model based on FST input. We anticipate collaboration with both simulations efforts and data studies. The model is designed to facilitate easy inclusion of additional data in response to FST needs (e.g., wave data).

Vania Jordanova/Los Alamos National Security, LLC
Investigations of Magnetosphere-Ionosphere Coupling with RAM-SCB-E

The main research goals of this investigation are to provide better understanding and improved predictive capability of energetic ion dynamics in the coupled magnetosphere-ionosphere system. In particular, we will investigate 1) how are heavy ions transported from the ionosphere and what is their distribution in the magnetosphere, and 2) how does the ionospheric conductivity vary with space and time and what is the feedback on the global E field and ion circulation. These are key objectives of this NASA/LWS solicitation, Focused Science Topic (FST) (3) "Ion Circulation and Effects on the Magnetosphere and Magnetosphere-Ionosphere Coupling".

The methodology includes a combination of several physics-based models used to study the coupled magnetosphere-ionosphere system driven by solar activity, and analysis of space-borne and ground-based observations. First, we will simulate the ion outflow from the ionosphere using a newly developed at LANL large-scale particle tracing model (PTM) driven by dynamic electric and magnetic fields from state-of-the-art models described below. The supply of heavy ions to the magnetosphere as a function of source location, solar and geomagnetic activity will thus be investigated. Second, a unique transport code, a ring current-atmosphere interactions model with self-consistent magnetic field and (recently added) self-consistent electric field (RAM-SCBE) will be used to simulate the subsequent injection of particles (H+, He+, O+ ions and electrons) from the plasma sheet into the inner magnetosphere and their precipitation to the ionosphere. Third, we will couple RAM-SCBE with a two-stream electron transport code (GLOW) to compute the height-dependent electric conductivity, given the electron precipitation from the ring current model. This will allow for a self-consistent calculation of the ionospheric conductance (the height-integrated electric conductivity) that is crucial in regulating both the ionospheric electrodynamics and the magnetospheric dynamics. We will simulate geomagnetic storms of various strengths with the newly coupled modeling framework (PTM/RAM-SCBE/GLOW) and compare results with the traditional empirical approach, which is commonly used in global simulations, to evaluate the effects of the self-consistent feedback and answer the science questions listed above. In order to validate the predictive capabilities of our model and identify where improvements are needed, simulation results will be compared with in situ and ground-based measurements at many stages of the modeling cycle. Van Allen Probes will thus be used for validation of magnetospheric particle fluxes, DMSP and NOAA satellites for particle precipitation, and ground-based ionospheric measurements for validation of the ionospheric parameters.

This research is highly relevant to the strategic goals of the NASA/LWS and the National Space Weather programs to develop predictive models of energetic particle dynamics and electrical current systems, and to be able to forecast adverse activity that could be dangerous to technologies and humans in space and on ground. RAM-SCBE extends an inner magnetosphere model (RAM-SCB) that has a proven history as a component in the Space Weather Modeling Framework (SWMF), and therefore this proposal can directly lead to an improved configuration of the operational SWMF that is currently used to predict ground magnetic perturbations at NOAA/SWPC.

This project will result in an improved understanding of magnetosphere-ionosphere coupling and a comprehensive model with space weather applications. The main contributions to the FST will include sharing the scientific results and simulation outputs (e.g., ion distributions and ionospheric conductance maps) from our model with the other researchers from the FST team, as well as help with the organization and active participation in the FST team meetings. All products from this research will be shared with the space science user community.

Suk-Bin Kang/Catholic University Of America
Quantifying deep penetration of energetic electrons and ions in the inner magnetosphere during extreme storms

Science Question:
SQ1. What are the global distribution and dynamics of electric and magnetic fields in the magnetosphere and ionospheric potential during extreme events?
SQ2. What causes the deep penetration of energetic electrons and ions to low L-shells during extreme events?

Relevance:
The proposed study is relevant to Focused Science Topic (4) Understanding Physical Processes in the Magnetosphere--Ionosphere / Thermosphere / Mesosphere System during Extreme Events. This proposal is also relevant to LWS program objective (1) Understand solar variability and its effects on the space and Earth environments with an ultimate goal of a reliable predictive capability of solar variability and response.

Energetic electron and ion transport in the magnetosphere and ionosphere is predominantly determined by global electric and magnetic fields. The plasma pressure produced by energetic electrons and ions also contributes to changing magnetic field configurations and therefore affects the ionospheric potential. Deep penetration of energetic electrons and ions in the inner magnetosphere can impact mid-latitude spacecraft and mid-latitude ground-induced currents (GICs). However, both empirical and pure magnetohydrodynamic (MHD) models often fail to reproduce polar cap potentials and magnetic field configurations due to extreme solar wind and ring current conditions. Furthermore, radial diffusion coefficients derived from statistical electric and magnetic fluctuations are not valid for extreme geomagnetic conditions, making it even more difficult to predict particle transport during extreme events. Thus, these limitations motivate us to use a state-of-the-art model of two-way-coupled global MHD and inner magnetosphere to answer the two science questions

Methodology:
[1] Use the Space Weather Modeling Framework (SWMF) which couples the Comprehensive Inner Magnetosphere and Ionosphere (CIMI) 4-D bounce-averaged kinetic ring current model with the Block Adaptive Tree Solarwind Roe-type Upwind Scheme (BATS-R-US) global MHD magnetospheric model to self-consistently simulate the global electric and magnetic fields, and the ionospheric potential. CIMI will also be used to simulate the transport of ring current electrons, ions, and < 1 MeV radiation belt electrons.
[2] Use a guiding-center test particle code to simulate transport of highly and ultra-relativistic electrons that rarely affect the global electric and magnetic field configuration.
[3] Compare observations with simulations and carefully compare between the two simulation models each other to validate and quantify the limitations of each model.

Lynn Kistler/University of New Hampshire
Factors that Control the Ion Composition of the Plasma Sheet and Ring Current

The goal of this proposal is to address the factors that affect the heavy ion content of the magnetosphere, in particular O+ and the O+/H+ ratio, from an observational perspective, focusing on the hot (>20 eV) ions. Specifically, we will address the following questions:
- What are the factors that affect the composition of the ion outflow?
- What factors determine the combination of solar wind and ionospheric sources that reach the plasma sheet?
- What is the time scale of the transport of ionospheric heavy ions through the magnetosphere during a storm?

The magnetospheric plasma comes from two basic sources, the ionosphere and the solar wind. The hot ionospheric plasma predominantly escapes into the magnetosphere from two locations: the dayside cusp and the nightside aurora. The cusp ions flow over the polar cap and into the lobes before entering the nightside plasma sheet. The nightside auroral ions have direct access to the nightside plasma sheet. Because of their different transport paths, the ions from these two locations have experienced different acceleration and heating, and their contributions to the plasma sheet vary with radial distance. The solar wind contribution also varies, and although the solar wind does not contain O+, an enhanced solar wind source will change the O+/H+ ratio. Thus, the interplay of the dayside and nightside ionospheric sources and the solar wind must all be taken into account to understand the ion composition changes.

Methodology
The project will use a combination of statistical studies and case studies to address the interplay of the different sources. The FAST/TEAMS data will be used to determine how the ion composition of auroral outflow depends on solar zenith angle and EUV, as well as Poynting flux and electron precipitation. This work will capitalize on a study already

completed using FAST that determines the outflow as a function of Poynting flux and electron precipitiation for different solar zenith angles, and add the 3D FAST/TEAMS pitch angle distributions for a definitive determination of the composition of the outflow. The study can then be expanded to more years to determine solar cycle dependence. The determination of the fraction of solar wind and ionospheric sources that reach the plasma sheet will be done with a combination of AMPTE/CHEM data and MMS/HPCA data. AMPTE/CHEM provides a unique dataset, not duplicated on more recent magnetospheric missions, that includes both the mass and charge state of an ion. This allows solar wind minor species, such as high charge state ((Q>3) oxygen to be measured. Using this dataset the relative contributions of the solar wind and ionospheric plasmas to the 7-9 Re plasma sheet can be determined as a function of geomagnetic activity. While MMS/HPCA cannot measure the high charge state oxygen, it can measured the solar wind ion He++. The He++/H+ ratio in the plasma sheet from MMS will be compared with the solar wind He++/H+ ratio to also determine the fraction of the plasma sheet that is from the solar wind. Combining these measurements with the results from AMPTE, an estimate can also be made of the contribution of the solar wind to the EIS measurements of oxygen. Knowing how much of the H+ and oxygen comes from the solar wind, we can then determine the contribution of the ionospheric component as a function of radial distance. This will be compared with the expectations of models of ion transport to the plasma sheet.

Final, to study the transport times of ionospheric ions, we will identify events in which MMS, Van Allen Probes, and, in some cases, Cluster have measurements that can be used to track the access of O+ to the plasma sheet, and from there to the inner magnetosphere during storms. These observations will be compared with modeling results from the team to test which models are best able to reproduce the observed spectra with the observed timing.

David Lario/The Johns Hopkins University, Applied Physics Laboratory
The Role that Coronal Shocks and Cross-Field Particle Transport Processes Play in the Observation of SEP Events

CONTEXT: Interpretations proposed in the literature to explain the spread of solar energetic particles (SEPs) in the heliosphere after the occurrence of a solar eruption include: [1] Cross-field transport processes in the solar corona and interplanetary (IP) space; [2] broad particle sources associated with coronal and IP shocks capable of accelerating and injecting particles into extended regions of the heliosphere; and/or [3] complex magnetic field configurations in the corona or IP space that allow SEPs injected from a narrow source to reach distant heliospheric locations. Our research effort will analyze the role that coronal shocks and cross-field transport processes play in the observation of SEPs at different locations of the inner heliosphere.

SCIENCE QUESTIONS AND OBJECTIVES: Under the paradigm that the main agents in the acceleration of SEPs are shocks initially driven by coronal mass ejections (CMEs), the observation of SEPs requires that, in absence of SEP cross-field diffusion, [1] the shock establishes magnetic connection with a spacecraft (S/C), [2] the region of the shock front magnetically connected with the S/C provides the conditions necessary for an efficient acceleration and injection of particles, and [3] SEPs propagate along IP field lines to reach the S/C. We propose a well-delimited program aimed at analyzing whether these conditions are met and thus determine the role that coronal shocks have in the SEP release onto different regions of the corona and IP space. We include also the contribution that cross-field transport processes in the corona and IP space have in the observation of SEP events. The proposed questions are: (1) What is the role played by coronal shocks in the release of SEPs? (2) Are the conditions at the shock appropriate for SEP acceleration? (3) What is the contribution of cross-field transport processes in the spread of SEPs?

METHODOLOGY: We will focus on SEP events associated with CMEs. We have developed a robust technique that allows us to determine from multipoint remote-sensing observations the extent, shape, kinematics and density compression ratios of coronal shocks. We will use coronal magnetic field MHD models and PFSS results to determine (1) the magnetic connection between S/C and coronal shocks, (2) the properties of the shocks, and (3) the configuration of the coronal field where SEPs and shocks start propagating. We will use this technique to analyze a sizable number of events and define the time-dependent properties of the shock and the SEP coronal transport processes that control the release of SEPs into space. The derived SEP injection regions will be used as input of a well-tested SEP transport model to compute SEP intensities and anisotropies at remote locations in IP space. Comparison between model predictions and observations will delimit the roles played by the shock and SEP transport processes.

RELEVANCE AND CONTRIBUTIONS TO THE FOCUS TEAM EFFORT: Significant progress "Toward a Systems Approach to Energetic Particle Acceleration and Transport on the Sun and in the Heliosphere" requires a deep knowledge of the role that coronal shocks play in the acceleration and injection of SEPs and the contribution that SEP transport processes have in the observation of SEPs. Throughout the project we will provide [1] detailed characterization of the coronal shock properties as a function of time, longitude and latitude, to be used as precursors of SEP predictive capabilities, and [2] SEP transport modeling in the corona and IP space necessary for interpreting SEP observations and constraining the mechanisms responsible for the extent of SEP events. Our experience in multi-spacecraft analysis of solar transient events is a crucial asset for the success of the team. Our work targets several Heliophysics and space weather strategic goals such as understanding the particle acceleration mechanisms in solar eruptions and determining the near-Earth radiation environment.

Gang Li/University Of Alabama, Huntsville
3D Modeling of Particle Acceleration and Transport at a CME-driven shock

Science goals and objectives:
We propose a 4-year project that addresses the 2017 LWS Focused Science Topic (FST): Toward a Systems Approach to Energetic Particle Acceleration and Transport on the Sun and in the Heliosphere. We will combine a well- established 3D MHD code Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS) and a newly improved Particle Acceleration and Transport in the Heliosphere (iPATH) model that describes the acceleration of energetic particles at shock waves and their subsequent transport in the interplanetary medium to provide a more realistic multi-dimensional temporal description of particle acceleration at CME-driven shocks. We will focus on the following science questions:

1) How does shock geometry affect the acceleration process? Along a shock surface, are regions with a quasi-parallel configuration more efficient particle accelerators than regions with quasi-perpendicular configurations?
2) What is the cause of the systematic heavy ion (Q/A) dependence of spectral breaks?
3) What is the effect of perpendicular diffusion on the observed particle time intensity profile and particle spectra at different locations in the interplanetary medium?

Methodology: Two major numerical codes, both developed at UAH, will be combined in the proposed project. The MS-FLUKSS is a suite of codes solving the coupled MHD and kinetic Boltzmann equations in the adaptive mesh refinement (AMR) framework. It will be used to describe the large-scale heliosphere into which a CME will be driven. We drive simulations using photospheric vector magnetograms. This makes it possible to implement a mathematically-consistent, characteristic boundary conditions and create a suitable background solution for the CME propagation. We have developed a novel method to insert CMEs into the solar wind. It is based on the generalized Gibson-Low approach that uses multi-viewpoint remote observations of CMEs by SOHO and STEREO. The MS-FLUKSS ability to track surfaces passively propagating with the solar wind makes it easy to develop AMR algorithms for precise tracking of a CME and related shocks as they propagate toward Earth. The iPATH model numerically follows particle acceleration and transport in the heliosphere. The current iPATH code is a 2D particle acceleration model that extends the earlier PATH model, developed originally by Zank et al (2000). We propose to further extend iPATH to 3D. This will be done with an "operator split" in the two non-radial directions based on the geometry of the CME-driven shock relative to the local interplanetary magnetic field. To obtain instantaneous particle spectra at the shock, knowledge of the local magnetic field geometry and plasma density jump is required, which are derived from MS-FLUKSS.

Contributions to the Focus Team Effort: Understanding particle acceleration and transport is central to describing the origin of gradual SEP events. By combining a mature, well tested and state-of-the-art 3D MHD code with a mature, well-tested, and state-of-the-art particle acceleration and transport code, the 3D iPATH model, we will provide a major advance to both the physics and modeling of gradual SEP events. Our model will yield time intensity profiles and particle spectra as time-dependent functions of longitude, latitude, and radial distance, making our results highly relevant to the upcoming Parker Solar Probe and Solar Orbiter missions.

Relevance: This proposed work addresses the LWS FST "Toward a Systems Approach to Energetic Particle Acceleration and Transport on the Sun and in the Heliosphere." Specifically, the proposal addresses the goal of identify[ing] the mechanisms by which impulsive energetic particle events or gradual events of large angular extent occur and the goal of understand[ing] the relative roles of flares and CMEs in producing energetic particles as well as the underlying acceleration mechanisms.

Mark Linton/Naval Research Laboratory
Investigating Magnetic Flux Emergence with Modeling and Observations to Understand the Onset of Major Solar Eruptions

Science Goals and Objectives

We propose to address the Living with a Star Focused Science Topic (LWS FST): ``Understanding the Onset of Major Solar Eruptions." To achieve this, we propose to investigate the injection of free energy and helicity in the corona, and the subsequent triggering of major solar eruptions, focusing on the emergence of magnetic flux into the corona. Our goal is to understand how emerging magnetic flux either injects helicity and free energy into the corona to generate eruptions, or destabilizes pre-existing structures so that they erupt. To achieve this, we will investigate flux-emergence sources of active region eruptive capacity by simulating the emergence of magnetic flux into the corona in eruptive configurations. In parallel, we will use these simulations to develop observables for predicting the occurrence and timing of eruptions. We will use FST team observations to test these metrics on both eruptive and non-eruptive ARs.

Methodology:

Our proposed methodology is to simulate eruptions driven by flux emergence in two prominent theoretical eruption scenarios: the formation of unstable sheared fields and flux ropes via flux emergence; and the destabilization of pre-existing sheared fields and flux ropes via flux emergence. The configurations studied will include both the ``breakout" and the ``torus instability" eruption paradigms. To simulate these scenarios, we will use both the LaRe3d (Lagrangian Remap in Three Dimensions) code and the MAS (Magnetohydrodynamics outside A Sphere) code.

With these simulations and analyses, we propose to answer the following questions:

Question 1: How does flux emergence inject free energy and helicity into the corona?

What are the critical magnetic configurations which are built up by emerging magnetic flux into pre-existing coronal fields? We will use our simulations to determine the observable signatures of this buildup of free energy and helicity by flux emergence, and to determine which simulated configurations of emerging flux do, or do not, lead to eruptions.

Question 2: How does flux emergence trigger eruptions?

What aspects of emerging flux act as the trigger which sets off an eruption? By freezing the emergence of flux at earlier and earlier times in our simulations during eruptions until the eruption no longer occurs, we will isolate the time at which this trigger is injected into the corona.

Question 3: How can the models explored in this project be used to develop predictive observables for eruptions?

Using the modeling results, we will establish a well-defined set of rules for determining, from observed magnetic field and velocity signatures, when an eruption-driving flux emergence event is occurring on the Sun.

We will combine the insight gained from answering these questions to develop an understanding of which key factors energize pre-eruptive active regions and lead to the onset of major solar eruptions. This project will therefore advance the LWS goal of ``Developing physics based understanding for predicting electromagnetic,
particle and plasma outputs driving the solar system environment..."
(Strategic Science Area 0).

Benjamin Lynch/University of California, Berkeley
Modeling the Causes and Consequences of Solar Eruptive Events that Drive Major Coronal Mass Ejections

A central goal of NASA's Living With a Star (LWS) Program is to develop the scientific capabilities necessary to understand and predict significant changes in the near-Earth space environment. The large solar flares and coronal mass ejections (CMEs) that produce the most severe space weather disturbances are powered by the rapid release of energy stored in the coronal magnetic field. Energy buildup and release in the low corona are driven both by the emergence of new flux through the solar photosphere, by the changes of the distribution of already-emerged magnetic flux, and the corresponding coronal evolution.

We propose a comprehensive series of data-inspired and data-driven numerical MHD simulations of energized active regions (ARs) that are observed to erupt with large flares that result in energetic coronal mass ejections. The aim of our simulations and analysis will be to obtain quantitative measures of the causes and consequences of solar eruptive events to answer the main scientific question: How do energized active region fields erupt?

Our simulations will be designed to address the following specific science questions:

(1.) What is the role of the photospheric boundary flows and vector magnetic field evolution in triggering the CME initiation?

(2.) What is the role of the adjacent and overlying AR and larger global-scale magnetic field in facilitating or inhibiting the CME initiation and eruption?

(3.) What are the roles of flux-cancellation and flux emergence in the energization and destabilization of AR configurations?

We will perform a set of 3D spherical MHD simulations with the RADMHD code based on a set of initial, energized magnetic field states obtained by the magneto-frictional (MF) modeling of a handful of eruptive ARs obtained via the Coronal Global Evolutionary Model (CGEM) framework. We propose to investigate the MHD response of these ARs and their surrounding flux systems to both idealized and observed boundary flows by leveraging the CGEM-MF capabilities to generate data-driven, energized magnetic field configurations observed by the Solar Dynamics Observatory.

The RADMHD boundary flows will be calculated via the PDFI electric field methods pioneered by our group in the development of the CGEM project. These energizing flows will generate Poynting flux, increase the free magnetic energy, inject relative magnetic helicity, and evolve the spatial distribution of magnetic energy density throughout the simulation volume. We will test various flow and field evolution driving on the same CGEM-MF configurations in RADMHD computational domains of varying sizes to investigate: the contributions of the driving and subsequent evolution of the energized and overlying flux distributions; how much external, breakout-like reconnection or flux-cancellation/tether-cutting reconnection contributes to the AR destabilization and eruption; and how much flux emergence contributes to the energization and subsequent eruption.

Our multidisciplinary data analysis and data-driven modeling project directly supports the LWS FST Understanding the Onset of Major Solar Eruptions. Our proposed work will contribute to the FST by calculating the relevant physical observables associated with the energization and eruption of CME-producing ARs in both observations and our corresponding simulation data. We will explore the parameter space of energized AR systems right at the onset of their loss-of-equilibrium by modeling the full MHD evolution of these systems under different driving conditions and flux evolution scenarios.

Additionally, the proposed work addresses a number of the science goals identified in the Solar and Space Physics Decadal Survey, such as "determine the origins of the Sun's activity and predict the variations of the space environment," "determine the interaction of the Sun with the solar system," and "to discover and characterize fundamental processes that occur within the heliosphere."

John Lyon/Dartmouth College
Modeling oxygen outflow: its origins and energization

Science Goals and Objectives:
Heavy ion outflow - mainly oxygen - is an important element of the magnetosphere-ionosphere system. For example, heavy ions may become a major or even the dominant plasma constituent both in terms of their number and energy density in the plasma sheet and ring current during disturbed times. However, the mechanisms by which oxygen is raised, accelerated and heated remain uncertain. This proposal will use modeling in conjunction with data inputs to characterize the key mechanisms of O+ upwelling, acceleration and heating. In particular, we will investigate how self-consistent drivers of plasma and neutral motions, including the solar wind-magnetosphere interaction, regulate outflow. This is motivated by the fact that both wave and particle energy flows within the magnetosphere are driven by the interaction with the solar wind. In addition, the state of the neutral atmosphere affects amount of oxygen available and its possibility of outflow. We will further investigate how O+ is energized to escape velocity and beyond, and what determines the O+ outflow flux. Generally, the ionospheric ambipolar field is sufficient to cause oxygen to upwell but insufficient to have it escape let alone achieve energies seen within the magnetosphere. Does outflow itself create feedback loops with the rest of the magnetosphere and ionosphere that affect outflow? Studies have shown that oxygen outflow may cause the magnetospheric sawtooth events. Are there other ways in which outflow either self-regulates or causes magnetospheric phenomena which indirectly control outflow? The use of a fully self-consistent model for magnetosphere including ionospheric outflow allows us to test various mechanisms for oxygen outflow through comparison with data and to use that data as well to produce causal relations for the outflow.

Methodology:
This proposal attacks these questions though an advanced model for polar wind outflow coupled to simulation of the solar wind-magnetosphere-ionosphere system. The key elements of the model chain are the Ionosphere/Polar Wind Model (IPWM), including treatment of an energetic O+ fluid population accelerated by wave-particle interactions, the multifluid LFM model, and the ionospheric electrodynamic coupler MIX including embedded models of diffuse, monoenergetic and broadband electron precipitation which influences the ionospheric electrodynamics and the source populations for ionospheric outflows. IPWM can use various models for the neutral thermosphere in order to investigate the interaction of neutral dynamics with oxygen outflow. An additional capability is ion tracking through the model fields. These traced particles can be

subjected to parameterized wave-particle interactions to test models. The planned research will attempt to isolate elements leading to outflow by changing parameters, such as sub-grid scale heating, and assessing the effects on the outflow and the magnetospheric system. A major part of that assessment will be data-model comparison. In addition, we will examine sources, such as the FAST data, to probe for direct contributors to or proxies for oxygen acceleration.

Proposed Contributions to the Focus Team Effort:
A wide range of data relevant to the focus topic is available from NASA missions. These include FAST measurements at low altitude, MMS dayside and tail measurements, data composition data from Cluster and Geotail, and inner magnetosphere data from Van AllenProbes. Ionospheric and related ground data is also available from SuperDARN, SuperMAG, and AMPERE. Our fit within the team is to provide a first-principles modeling context for the effort. Having a comprehensive model of outflow will allow observations taken at one point to be related to data from another region. With aid of other team members observational data will be used to constrain the outflow models. One specific milestone will be an improved causal model for oxygen outflow for system-wide studies

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Meers Oppenheim/Boston University
Conductance Effects on Global Magnetosphere-Ionosphere Evolution during Storms and Superstorms

Science goals and objectives: In order to accurately model extreme space weather events, Magnetosphere-Ionosphere-Thermosphere (MIT) simulators need to accurately model high latitude conductivities. This requires incorporating effects from small-scale but intense physical processes such as precipitation and ionospheric turbulence. During storms and super-storms, precipitation dramatically increases the ionospheric E-layer plasma density and, hence, the conductivities. Also, the magnetosphere forces enormous currents through the ionosphere such that it becomes turbulent, causing major changes in the conductivities. These effects also dramatically increase the total energy and momentum transferred to the ionosphere and thermosphere. Researchers have shown that while simulations accurately model changes in the MIT system during typical day-to day variations and moderate events, they cannot accurately model the structure of the MIT during severe storms. To do this, researchers will need to upgrade the conductance models in these simulators, most notably the precipitation and ionospheric turbulence models. This is particularly true for extreme events when precipitation and turbulence will become widespread and intense.

Methodology: This project will incorporate modern physics-based models of precipitation and their interactions with the high latitude turbulent ionosphere into the conductivity and Joule heating of the coupled LFM-RCM-TIEGCM MIT simulator. This project will bring together experts in kinetic theory, collisional PIC, and global simulations of the MIT system. The major tasks will include improving parameterizations of kinetic theories and simulations of precipitating electrons including the effects of multiple collisions, reflection, and photoionization. It will also evaluate the effects of this precipitation upon ionospheric turbulence using massively parallel PIC simulations. The corresponding parameterized corrections will be included in the momentum and energy equations within the NCAR TIEGCM model with subsequent incorporation of resulting enhanced conductivities into the global MHD simulation. The newly improved simulator will be used to explore the behavior of the coupled MIT system during extremely disturbed geophysical conditions and the results will be checked against ionospheric observations.

Proposed Contributions to the Focused Science Team Effort: This project provides a strategic capability necessary in fulfilling the LWS program objective: "Understand solar variability and its effects on the space and Earth environments with an ultimate goal of a reliable predictive capability of solar variability and response." It will fill a critical gap that in "understanding physical processes in the magnetosphere--ionosphere / thermosphere / mesosphere system during extreme events." The simple conductance models used by today's geospace simulators need critical improvements to accurately model current flows through high latitudes during even moderate storms. This will help fulfill the second goal of the Heliophysics Decadal survey: "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." The anticipated results of the project will help the Heliophysics community address two fundamental Science Questions posed in the 2010 Science Plan for NASA's Science Mission Directorate: (1) How do the Earth and Heliosphere respond? (2) What are the impacts on humanity?

Antti Pulkkinen/NASA Goddard Space Flight Center

Physics-based modeling of the magnetosphere-ionosphere-thermosphere-mesosphere system under Carrington-scale solar driving: response modes, missing physics and uncertainty estimates

This proposal will address the Focused Science Topic "Understanding Physical Processes in the Magnetosphere--Ionosphere / Thermosphere / Mesosphere System (M-ITM) during Extreme Events." We will investigate the global physics-based modeling of the magnetosphere-ionosphere (M-I) system under extreme solar driving conditions such as those experienced during the Carrington storm of 1859. The specific focus of the proposed work is to advance global modeling of the ground magnetic field (delta-B) variations under extreme solar driving conditions. To this end, we will provide quantifiable advancements in modeling of the spatiotemporal delta-B structures. The delta-B focus provides a direct connection to the global M-I dynamics as the field variations on the ground are an aggregate of all the electric currents that operate in the geospace environment. Delta-B variations are also the primary driver of geomagnetically induced currents (GIC) that flow in long ground-based technological conductor systems such as power grids. Our work thus directly supports national space weather needs via improved understanding of the phenomena that cause GIC.

Two target phenomena of specific high-interest to space weather will be the focus of this work:

i) Auroral boundary expansion during extreme events. Auroral boundaries determine the locations that are exposed to the most extreme delta-B fluctuations and GIC.
ii) Spatiotemporal localization during extreme events. Spatiotemporally localized delta-B are perhaps the most significant cause for large-amplitude GIC.

The target phenomena are used to address three key science goals:

1) Quantification of model uncertainty under extreme driving conditions. The uncertainties and variability are some of the most important and yet poorly addressed characteristics of any space weather modeling effort. We will develop methodologies for quantifying the M-I modeling and specifically delta-B uncertainties. Methodologies for both normal storm conditions and extreme storm conditions not seen in modern observations are explored.
2) Key missing physics in modeling extreme storms. We will identify possible missing physical elements in our modeling of the M-I system under extreme driving conditions.
3) Changes in fundamental system response modes. With information from goals 1) and 2), we will explore possible changes in the M-I dynamics under extreme Carrington-scale solar driving not seen in modern delta-B observations.

The work is carried out using a large number of M-I simulations and analysis of the corresponding modeled and observed delta-B variations. Careful coordination between the goals 1-3 in the context of the target phenomena allows new light to be shed on the physical processes behind important GIC-related phenomena. Our work will also generate quantifiable evidence of progress toward more accurate simulation of extreme space weather events. Our team will be integrated with the Focused Science Team (FST) Effort via provision of delta-B simulations capacity and recommendations for further model development efforts by the other FST teams. All simulations carried out in the project will be made publicly available via Community Coordinated Modeling Center (CCMC). Further, we will coordinate our work with NOAA Space Weather Prediction Center (SWPC) to ensure that operational considerations are take into account in addressing the delta-B features (operations-to-research) and to allow transition of the new information back into operational implementation of the M-I models at SWPC (research-to-operations).

Ennio Sanchez/SRI International
Tracing the Height-dependence of Upward Acceleration in Ion Outflow

Objectives and Significance. The extraction of plasma from the atmosphere is one of the most important effects of space weather, on Earth and any other planet that has an atmosphere. The process of extraction likely results from a sequence of mechanisms that start accelerating upward the ions in the F-region and continue to accelerate them well above it. The contribution that each mechanism has on the ion acceleration is not well determined. Furthermore, the wave modes' identification as well as the height dependence of their amplitude is not well established. This project will take full advantage of ground-based assets (incoherent scatter radars, ISRs), spacecraft assets (Fast Auroral SnapshoT, FAST, and Akebono), and models (Ionosphere/Polar Wind Model, IPWM, and Dynamic Fluid-Kinetic, DyFK) to trace for the first time the ionospheric populations from their source -the F-region of the ionosphere-into high altitude with the objective of quantifying the contribution of the different likely acceleration mechanisms and the ability of outflow models to predict the observed fluxes. The team assembled for this project has the expertise and experience in incoherent scatter radars (ISRs), fluid and hybrid models, FAST and Akebono wave data analysis, to successfully carry out all tasks of the project.

Methodology. We will construct an empirical statistical model of the variation of wave amplitude with altitude using FAST and Akebono wave data. We will use this model to establish mean and variance of waves' amplitudes with altitude that can be used to constrain the allowable changes in the ion extraction models. We will employ two different models of ion outflow: The IPWM and the DyFK model. We will identify all events in the ISR databases (Sondrestrom and EISCAT) that contain signs of up-flow in the F-region while either FAST or Akebono is near to the ISR location. We will use the ISR measurements in the F-region to initialize the out-flow models from below and spacecraft measurements to constrain them from above, and model the ion fluid (or particles) motion along the flux tube while convecting the flux tubes horizontally. We will compare the flux and particle distribution predicted by the outflow models (with the wave properties from the FAST-Akebono empirical model as input) with the flux and particle distribution observed by the spacecraft, and iteratively adjust the wave-particle interaction (WPI) inputs to the models until satisfactory agreement is achieved within the error limits imposed by the FAST-Akebono empirical model. We will compare the final solution for the WPI inputs to the wave observations from the spacecraft and will repeat the comparison methodology for events at different locations of the polar ionosphere and levels of geomagnetic activity.

Impact of the Work. The empirical model of wave power versus altitude will help reduce the large uncertainty in the currently assumed variation of wave power with altitude, region, and geomagnetic activity. This investigation will also provide a direct estimation of the prediction error that can be assigned to each of the models and the quantification of the adequacy of the assumption of ion cyclotron resonance heating by extremely low frequency (ELF) waves. The improvement in the specification of ion acceleration in the IPWM model will benefit all other work using that model, including global modeling efforts using IPWM coupled to the MultiFluid Lyon-Fedder-Mobarry (MFLFM) global magnetospheric model. Past experience with the global coupled model has shown that the coupled system dynamics and global magnetic field fluctuations are highly sensitive to the local details of how ion acceleration is regulated. Therefore, an improved understanding of local ion acceleration is expected to have a significant impact on our ability to predict global dynamics.

Antonia Savcheva/Smithsonian Institution/Smithsonian Astrophysical Observatory
Physics-based Understanding and Data-constrained Simulations of CME Initiation and Propagation

Physics-Based Understanding and Data-constrained Simulations of CME Initiation and Propagation

There are multiple factors that determine the stability of active regions (AR) and how much energy they can store, which on the other hand determines the properties of the eruption. For this purpose we plan physics-based parameter study of Titov-Demoulin (TD) flux rope (FR) equilibria with and without boundary motions in an idealized 3D MHD simulation that will address the following science questions:
1. What are the factors that determine the stability of TD FRs in different topologies?
2. How much energy and helicity is stored in each case and what are the parameters of the eruptions produced from the loss of equilibrium?
3. What factors determine if an eruption is failed, or if successful ý its initial parameters?

Based on identifying typical topologies, classes of boundary motions, and equilibrium parameters, we will aim at identifying pre-eruptive configurations that possess similar characteristics based on data from the current fleet of NASA space missions like SDO, Hinode, IRIS, STEREO, and LASCO. We propose to perform data-constrained simulations of CME initiation and propagation starting from a realistic initial condition of these ARs with evidence of a FR that is on the verge of eruption. We can use this suite of state-of-the-art observations together with MHD simulations explore some long-standing science objectives:
1. Describe the CME initiation phase and the early phase of development of the CME.
2. Reproduce the observed three-part structure of CMEs as seen in LASCO and STEREO, and their in situ properties at 1AU by using data-constrained MHD simulations and data from WIND and DISCOVER.
3. Identify features that mark the configurations as ready to erupt and quantify the uncertainties in the location of the initiation site, the time period in which an eruption might happen, and predicted parameters of the ejecta. Estimate the probability that it could be a failed eruption.
To achieve these objectives we will address the following science questions:
1. What is the role of reconnection, instability, FR properties, and ambient field in the CME initiation process, i.e. how is the CME triggered?

2. How are the observed remote heliospheric and in situ characteristics of the CMEs with FRs at 1AU influenced by the initial properties in the corona and the subsequent propagation of the ejecta?
3. What are the predictive capabilities of the method and how can it be implemented for real time operations?

In answering the proposed science questions we will utilize NLFFF models of observed erupting active regions from the FR insertion method as initial conditions to the Space Weather Modeling Framework global MHD code. We will use this method to initiate and propagate more realistic CMEs to 1AU.

Contribution to the FST Effort
This proposal aims at addressing the LWS topic ýUnderstanding the Onset of Major Solar Eruptionsý by focusing specifically on both physics-based understanding and data-constrained simulations of AR eruptions which will shed light on the triggers and drivers of CMEs and their properties. One of our major milestones will consist in devising tools to determine markers of potential imminent eruptive behavior and how close to eruption the AR might be, and the subsequent CME properties with an estimate of the factors that contribute to any uncertainties on the prediction.
We propose to contribute to the team efforts by: (1) providing the results of our analyses of ARs and CMEs with a broad range of parameters and topologies from solar cycle 24; (2) sharing our physics-based understanding of the factors that affect AR stability and CME properties; (3) providing additional analyses of specific events as required by the team effort (e.g, AR QSL maps from our new fast 3D QSL code).

Philip Scherrer/Stanford University
Understanding the Role of Helicity Flux in Solar Eruptions from Active Regions

Magnetic helicity in solar active regions (ARs) is a volume-integrated quantity that quantifies complexity in ARs. As the main contributor to helicity in the corona, helicity flux through the solar photosphere drives solar activity and thus space weather. It has been suggested that there is an upper limit to the helicity in a volume. Because helicity dissipation in the corona is very slow, the only mechanism that effectively removes helicity from the corona is a coronal mass ejection (CME). When helicity is removed, more helicity can be injected into the corona from below. Thus, this ``helicity injection, ejection, replacement'' (HIER) scenario predicts variations of helicity flux with eruptions.

We propose to determine the relationship between helicity flux and solar eruptions. We will use SDO/HMI vector magnetic field and the velocity field inferred using the DAVE4VM algorithm to calculate helicity flux in active regions, combined with existing GOES data and CMEs catalogs to characterize eruptive activity.

The proposed project has three parts. First, we will improve the helicity flux calculation by implementing three additional processing steps to: A) minimize the 24-hour oscillation in HMI vector magnetic field data; B) determine the optimal temporal and spatial resolution of the input data; and C) improve the temporal consistency of disambiguation of the transverse vector field. Second, we will conduct a statistical study to characterize any helicity flux-eruptivity relationship. Third, we will compare the HIER model to alternatives (e.g., cumulative helicity flux matters, but not variability).

A) To reduce 24-hour variations we will employ an empirical relationship between magnetic field and Doppler velocity measurements using the method reported in our 2014 paper. The method demonstrably reduces the 24-hour power in the magnetic field data.

B) The calculation of helicity flux is sensitive to cadence, spatial resolution, and noise of the input data. The effects of these three characteristics are convolved each other. We will determine the optimal combination of parameters that provide the best results. The cadence of the HMI vector data can be as high as 90 seconds (135 seconds before April 2016) and the spatial resolution is 0.03 degrees. This leaves sufficient room to test and find the optimum.

C) The velocity field needed to calculate the flux is determined using DAVE4VM. The algorithm requires a time series of vector field data. Temporal consistency of the disambiguation is a key factor to assure derivation of a reliable velocity field. With CGEM support, we have already developed a scheme to remove temporal discontinuities in the transverse field direction. We will evaluate impact of this data improvement in flux calculations.

We will analyze helicity flux and solar eruptions in a large set of ARs. Active regions with no eruptions will also be included. We have already identified a sample of 535 ARs from HMI observation in 2010-2017, including 214 emerging active regions. This sample is sufficient for a statistical study.

The project is relevant to the Focused Science Topic (FST), "Understanding the Onset of Major Solar Eruptions." Our methods will also determine the energy flux in ARs. We will provide these improved measurements of energy and helicity fluxes calculated with the HMI vector field to the community. Other groups participating in the FST can use these key data products to drive simulations to understand process of buildup of free energy and instability, and evolution toward eruption. Theorists can also benefit from our products to understand magnetic energetics and instability. Our project directly supports a specified measure of success, "Production of critical derived data products such as Poynting flux, helicity flux injection, and free energy build up from the observables with appropriate estimates of uncertainties."

David Siskind/Naval Research Laboratory
Response of the mesosphere, thermosphere and ionosphere to extreme solar flare events

We propose a comprehensive study of the response of the mesosphere, thermosphere and ionosphere (MT-I) to extreme solar flare events. Our goal is to quantify how the electron density profile can be perturbed during these extreme events and assess the consequences of these perturbations for radio wave propagation through the ionosphere. Our study will include model calculations beginning with the solar flux emitted by the sun down through the thermosphere and F region ionosphere to the lowermost mesosphere/D-region base where enhanced ionization has been inferred in past events. Our calculations will include a new estimate of the soft X-ray and extreme ultraviolet (EUV) flare spectrum, appropriate to extreme flares, which combine the results from numerical simulations with empirical constraints. This flare spectrum will be used in a hierarchy of models of the ionosphere, including the 3D ionosphere/plasmasphere model (SAMI3), the National Center for Atmospheric Research (NCAR) Thermosphere-Ionosphere-Mesosphere General Circulation Model (TIMEGCM) and a 1D model of the D and lower E regions (OASIS). The TIMEGCM simulations will calculate the thermosphere composition, temperature, and wind in response to our new extreme Xray/EUV emission estimates; this data will be used as input to SAMI3 to calculate the ionosphere/plasmasphere response. The perturbation to the neutral nitric oxide abundance will be used as input to the OASIS D region model. We will validate our model simulations with previously observed extreme flares such as the October 2003 events and their associated perturbations to TEC, nitric oxide and D/E region electron densities. As part of our calculations, we will perform explicit calculations of radio wave absorption for large to extreme flare event using several Naval Research Laboratory developed radio wave propagation codes for direct comparison to available observations. We will then extrapolate our validated models to even more extreme events (e.g. Carrington type events) to address questions such as what might be the maximum electron densities that can occur in the ionosphere and to provide information that can aid the assessment of potential societal impacts of extreme space weather events.

Mikhail Sitnov/JHU/APL
Data mining for extreme space weather

Science goals and objectives: The overarching goal is to reveal distinctive features of the Earth's magnetosphere during extreme events (EEs) through empirical reconstruction of the geomagnetic field, electric currents and plasma pressure for superstorms (Dst index<-300 nT), taking into account their statistical peculiarity as EEs. We will compare distributions of the magnetospheric parameters with similar distributions for weaker storms and first-principle simulations to grasp the distinctions of EEs and their underlying mechanisms. Since EEs correspond to tails of the corresponding data distributions, their empirical pictures are strongly biased toward weaker events and their errors are large, making their interpretation particularly challenging. At the same time,

the error analysis can be used to improve the empirical picture of EEs, and this improvement is also one of the main objectives of this study, which is guided therefore by following science questions:
1) What are the distinctive features of spatial distribution and temporal evolution of the magnetic field, electric currents and plasma pressure during superstorms?
2) What are the key biases and uncertainties of empirical reconstructions of these quantities for EE activity level, and how can they be used to improve the empirical picture?
Methodology: The reconstruction will be made using the nearest neighbor (NN) data mining algorithm. In this approach, the state of the magnetosphere as well as its evolution are parametrized by the global activity parameters, Dst or Sym-H index, the solar wind electric field and their time derivatives. Then the magnetic field for a query event can be reconstructed using only a small subset of the whole historical database of magnetometer records. The resulting empirical picture, and in particular, distributions of the force-balanced plasma pressure, will be compared with pressure distributions retrieved from Energetic Neutral Atom (ENA) observations for EEs observed by the IMAGE mission in the period 2000-2004, to adjust the location of the pressure peak obtained by the NN method. Eventually, the amplitudes of empirical distributions will be adjusted based on the error and bias analyses to match the observed Sym-H values for the smallest possible NN bins. The empirical analysis of EEs will be complemented by similar studies of strong storms with Dst < -200 nT, including the strongest storms in the Van Allen Probes mission era, to validate pressure distributions using direct particle measurements and to improve the statistics of the pressure peak locations. The empirical model will be further extended to older superstorms in the period 1957-1991, when no solar wind monitors were operational, and hence no event-specific first-principles modeling is possible.
To understand the key physical processes specific for superstorms, their empirical picture will be compared with global simulations of the magnetosphere using the Lyon-Fedder-Mobarry (LFM) MHD model coupled with the kinetic Rice Convection model (RCM) of the ring current evolution. Further the RCM pressure will be replaced by its empirical analog inferred from the magnetic field distributions using the quasi-static force balance equation.
Proposed Contributions to the Focus Team Effort: The project contributes to FST #4 by providing an observational basis for identification of the key physical processes during EEs. The potential contributions to the FST's team effort will be empirical, first-principles and combined pictures of the magnetic field, currents and plasma pressure. These results will mark the milestones of the project. They can be used to improve understanding of the EE physics and provide direct assessment of the key Space Weather factors, such as the geomagnetically induced currents. The metrics of success will be derived from comparisons with ENA and in situ measurements.

O. St. Cyr/NASA Goddard Space Flight Center
Understanding the Connection Between Solar Energetic Particle Events and CME Dynamics in the Low Corona by Combining Observations from Mauna Loa Solar Observatory and Spacebased Coronagraphs

SCIENCE GOALS: This proposal addresses LWS TR&T 2017 Focus Science Topic (FST) #2. This is primarily an observational investigation comparing the characteristics of solar energetic particles (SEPs) with spacebased and groundbased coronagraph observations of the associated coronal mass ejections (CMEs). The work will provide new insights into the production of energetic particles in the low corona.

Studies based on spacebased coronagraph measurements in the middle corona indicate that CME dynamics provide information about the characteristics of the resulting SEP event. For example, the peak SEP intensity at a given location in space is dependent on the CME speed and direction [e.g., Kahler, 2001; Richardson et al., 2014] and correlated with the CME brightness [Kahler & Vourlidas, 2005]. Furthermore, the SEP spectral hardness appears to be related to the initial CME acceleration [Gopalswamy et al. (2015, 2017)], but this conclusion is based on proxies for the acceleration below the field of view of spacebased coronagraphs. By combining spacebased coronagraph observations with groundbased observations of the low corona, we will eliminate the need for proxies and measure CME formation and initial acceleration directly.

METHODOLOGY: We will study SEPs associated with CMEs detected since 1980 by coronameters at the Mauna Loa Solar Observatory that can measure directly the formation and initial accelerations of CMEs low in the corona (i.e., < 2 Rs). We will combine MLSO observations of the initial CME signatures with observations from spacebased coronagraphs, and we will then compare the CME characteristics with the properties of the related SEPs observed by spacecraft near Earth and elsewhere in the heliosphere. From an initial survey, at least 16 SEP events during 1980-1989 were associated with CMEs observed both by MSLO and the SMM or Solwind coronagraphs. The post-1996 data (SOHO & STEREO observations) have not been systematically examined, but over 60 SEPs associated with MLSO CME observations have been identified so far. Since there are at least 75 SEP events with spacebased coronagraph and MLSO coronameter observations of the associated CMEs from 1980-present, we expect to have a sufficiently large dataset to be able to significantly improve our understanding of the connection between CME and SEP characteristics.

RELEVANCE: Our investigation will provide direct measurements of CME formation and evolution low in the corona, where SEP acceleration is believed to occur. This investigation will likely be relevant to determining the spectral (and other) characteristics of SEPs. Both of these are solicited as types of investigations appropriate for this focused topic. The proposed work addresses the goal of the LWS program to provide a scientific understanding of the entire Sun-Earth system, almost to the point of predictability. It is also responsive to NASAs mission to protect human and robotic space explorers by improving timely forecasts of SEP events and their properties through CME observations.

CONTRIBUTIONS: We will provide direct measurements of CME formation and evolution low in the corona which are likely relevant to determining the spectral (and other) characteristics of SEPs. We will also provide such observations for case studies that are identified with other members of the FST. The PI and Co-I will provide analytical tools and interpretation of coronagraph and SEP measurements. All data used is publicly available including archival coronagraph data from MLSO, SMM, Solwind, SOHO, and STEREO, and SEP observations from IMP 8, Helios, WIND, ACE, SOHO, and STEREO.

METRICS: We will participate in regular telecons and face-to-face meetings with the other FS team members; we will present progress reports at relevant scientific meetings; and we will submit annual reports to HQ. We will discuss our progress and that of the FS team routinely with Collaborator Fry (NASA/SRAG).

Angelos Vourlidas/JHU/APL
Understanding the Genesis of Coronal Mass Ejections and Shocks via multi-viewpoint EUV and coronagraph analysis

This proposal addresses the Focused Science Topic: "Toward a Systems Approach to Energetic Particle acceleration and Transport on the Sun and in the Heliosphere" via the analysis of multi-view, high cadence EUV and White Light observations of the formation of CMEs and shocks in the solar corona. The study includes CMEs with and without SEPs integrating tightly with the final FST team.

Goals
Our goals are a focused subset of the overarching FST goals. Namely, we aim to develop a detailed observational understanding of the properties of the source regions of SEPs and to understand the relative roles of flares and CMEs in producing SEPs as well as the underlying mechanisms. Depending on the direction of the broader FST team we could also contribute in identifying the mechanisms by which impulsive or gradual SEP events of large angular extent occur.

Objectives
Our starting hypothesis, based on our early 3D reconstructions of EUV CMEs with STEREO/SECCHI and SDO/AIA, is that some CMEs undergo a fast (~1000 km/s), short-lived (< 10 mins) lateral expansion, during their formation. This hyper-inflation phase occurs during the flare impulsive phase, in close temporal proximity to the EUV wave and metric type-II formation and therefore could drive an early shock wave in the low corona. It can play an important role in particle acceleration and distribution.
To test this hypothesis, we undertake a thorough analysis of multi-view EUV and coronagraph observations of CME and shock/wave formation for SEP-associated events to address the following science questions:

- What is the 3D kinematic profile of the nascent CME? More specifically, do SEP-associated CMEs undergo a hyper-inflation phase during their formation?
- What are the 3D properties (kinematic and dynamic) of the CME and its associated wave from the low corona to 15 Rs?
- Can these properties account for the existence (or absence) of SEPs in a given event?

Methodology

We leverage existing analysis tools developed by our team and highly relevant to this problem. Namely, we use the 3D shock/CME reconstruction and wavelet-enhancement algorithms developed for the SECCHI analysis, and the Coronal Analysis of Shocks and Waves (CASHeW) framework developed for AIA analysis. Our approach comprises the following broad tasks:
- Use the CASHeW list of CME events (http://helio.cfa.harvard.edu/cashew/) to select a subsect of 20-30 CME-SEP events with good observational coverage in SECCHI+AIA.
- Select another set of ~10 events with similar EUV signatures but without (or possibly weak) SEP signatures to use as control group.
- Perform 3D reconstructions of the CME and wave in the EUV (<1.5 Rs) to extract the 3D speeds, sizes, directions, and expansion (radial & lateral) rates. For bright EUV events, extract the density across the shock and CME.
- Use models of the background magnetic field to estimate Alfvenic Mach number to estimate the shock strength.
- Perform similar analysis in the coronagraph images (SECCHI COR1 & COR2).
- Analyze the kinematics and connectivity to in-situ detectors on STEREO, ACE or Wind to understand the SEP temporal and spatial evolution.

Proposed Contributions to the FST Team Effort

Relevance: The proposal addresses three of the FST science objectives (see Goals)
Contributions to Team: We will provide 3D measurements of the temporal and spatial evolution, connectivity and compression rate of shocks and CMEs (1- 15 Rs), for ~30 SEP events. We will provide software and expertise to analyze specific events or simulations requested by the team.
Metrics: Extract the temporal and spatial evolution of the shock and CME from a statistically significant number of events. Estimate the compression rate in multiple locations (>2) across the shock below 15 Rs. Establish whether the hyper-inflation phase exists and whether it correlates with SEPs. Establish an empirical relationship between CME/shock kinematics and SEP production.

Lulu Zhao/Florida Institute Of Technology
An investigation on the roles of the shock acceleration and the interplanetary transport on the spectra of solar energetic particle events

Summary: Power-law spectrum is the most common type of spectra of energetic particles. However, the energy spectra of solar energetic particles (SEPs), observed by spacecraft located at 1 AU, often exhibit double power-laws with break energies ranging from one to tens of MeV/nucleon. The break energies for different ion species were reported to be correlated with particle charge-to-mass (Q/A) ratio. While the existence of single power-law has a strong theoretical foundation, there is no clear explanation for the double power-laws. Some literature attributes it to a mechanism of particle acceleration in a shock environment, while some suggest it is due to particle propagation from a remote source. In order to understand whether the double power-law features result from the source or the transport process from the Sun to 1 AU, we propose to undertake an investigation on the roles the shock acceleration and the interplanetary plays in breaking the energetic particle spectra.

Objectives: Our proposed research focuses on finding the origins of the double power-law spectral profile observed at 1 AU. Specifically, we will examine the following two hypotheses: (1) the double power-law energy profile is generated, close to the sun, due to the finite shock lifetime or size, or shock geometry in the standard shock acceleration theory; (2) the double power-law spectra are due to the transport process from the sun to 1 AU. If the first hypothesis is proved, we will examine the dependence of the break energies and their Q/A correlation on shock parameters and other conditions near the shock region. For a coronal mass ejection (CME) event, with the observed/simulated structures of the CME-driven shock, we will calculate the spectral shape of SEPs in the source region. The result can also serve as an input to the subsequent interplanetary transport process. If the second hypothesis is proved, we will examine the dependence of the spectral properties and its Q/A correlation on the interplanetary transport processes. Combining with the energy spectra obtained from other CME-driven shocks or solar flares simulations by other members of the team, we could forecast the energetic particle flux and total radiation at Earth.

Methodology: Both data analysis and numerical simulations will be performed. In our investigation of shock acceleration, we solve the focused transport equation for particle acceleration with self-consistent wave generations close to the sun. In the code, we will use observationally reconstructed CME shock or numerical simulation from the team as an input of plasma and magnetic field. The waves are used to determine parallel and perpendicular diffusion coefficients. The same focus transport equation will be used to calculation SEP interplanetary transport. By comparing the results of calculations with observations, we will analyze the spectral properties in a large number of SEP events observed by spacecraft. Specifically, we will analyze the spectral shape for whole SEP events as well as in various phases. The correlation between the spectral properties and the interplanetary magnetic field properties will be analyzed. With the combination of theoretical calculations and data analysis, we can gain a full understanding of various physical processes in modulating the energy spectra of SEPs.

Proposed Contributions to the Focused Science Team Effort: Our proposed work is directly related to the Focused Science Topic (2): toward a systems approach to energetic particle acceleration and transport on the sun and in the heliosphere. We will provide team members with the understanding of the physical mechanisms of the energy spectra breaks. We contribute to the determination of the relative importance of shock acceleration and particle interplanetary transport in modulating the particle energy spectra in SEP events. Our work will also contribute to the forecast of the radiation environment during solar energetic events.