Dear Heliophysics Community,

This summer, we solicited your input for Living with a Star (LWS) Focused Science Topics (FSTs) for ROSES 2019 and beyond. We received 46 topics from all areas of Heliophysics and many comments (see https://lwstrt.gsfc.nasa.gov/viewinput/2018/). We met in early July to carefully review all of these community suggested science topics, as well as topics submitted in previous years, keeping in mind the Heliophysics Decadal Survey goals, the overall Living with a Star goals, and the TR&T Strategic Science Areas (SSAs). Based on this, we have prepared a draft set of 19 Focused Science Topics, plus a Tools and Methods theme and a Sun-Climate theme, appended here for your inspection and comment. We considered all of the submitted topics very carefully and tried to create Focused Science Topics that included as much of this input as possible.

Please keep in mind that these are draft topics only. We are now soliciting community feedback on these drafts, as the next, critical stage of this year's process of generating science topics. All of these draft topics are posted on our website at https://lwstrt.gsfc.nasa.gov, with input boxes for comments and feedback on each individual topic, as well as on the overall process. The feedback site will be open for comments until October 19, 2018.

After this comment period closes, the committee will meet again to review the community feedback on the topics and, based on this feedback and on the Decadal Survey, LWS, and TR&T goals, to finalize the topics for our annual report to NASA Headquarters.

We look forward to your feedback on these draft topics.

Sincerely,
Mark Linton & Anthea Coster (co-chairs)
On behalf of the Living with a Star Program Analysis Group Executive Committee

Draft Focused Science Topics:

- Understanding the Impact of Thermospheric Structure and Dynamics on Orbital Drag
- Understanding and Predicting Radiation Belt Loss in the Coupled Magnetosphere
- Pathways of Cold Plasma through the Magnetosphere
- Understanding the Variability of the ITM System Due to Tides, Planetary Waves, Gravity Waves, and Traveling Ionospheric Disturbances
- The Variable Radiation Environment in the Dynamical Solar and Heliospheric System
- The Origin and Consequences of Suprathermal Particles
- Connecting Thermospheric Composition and Space Weather
- Understanding Ionospheric Conductivity and Its Variability
- Modeling and Validation of Ionospheric Irregularities and Scintillations
- Fast Reconnection Onset
- Extreme Solar Events -- Probabilistic Forecasting and Physical Understanding
- Connecting Auroral Phenomena with Magnetospheric Phenomena
- Understanding Space Weather Effects and Developing Mitigation Strategies for Human Deep Space Flight
- Solar Photospheric Magnetic Fields
- Magnetospheric and Ionospheric Processes Responsible for Rapid Geomagnetic Changes
- Coupling of Solar Wind Plasma and Energy into the Geospace System
- Combining Models and Observations to Study CME Plasma Energetics in the Inner Corona
- Atmospheric Evolution and Loss to Space in the Presence of a Star
- Hemispherical Asymmetries in Magnetosphere-Ionosphere-Thermosphere Coupling Processes: Fundamental Causes and Myriad Manifestations

Draft Sun-Climate Theme:

- Variability and Predictability of the Solar-Driven Earth System

Draft Tools and Methods Theme:

- Data Science and Analytics

Understanding the Impact of Thermospheric Structure and Dynamics on Orbital Drag

Introduction / Focused Science Topic Description:

Satellite Drag is the dominant error for predicting the accurate satellite orbits for all low perigee satellites; in other words, satellite drag is the primary error source for all Low Earth Orbit (LEO) spacecraft, and for satellites with elliptical orbits, where the perigee is in significant atmospheric drag regimes. In fact, for this latter category of satellite, the higher the apogee, the larger the density uncertainty. Accurate satellite orbits are needed for three primary reasons: collision avoidance, accurate pointing requirements for tracking, and reentry prediction. Collision avoidance requires actions that involve not only the spacecraft response to atmospheric drag but also the drag response of all the other space objects in LEO, especially debris. As the number of satellites in orbit is expected to increase exponentially and the lifetime of satellites and their debris increases, the need for accurate orbit prediction becomes critical.

Satellite drag is dependent on a number of factors, including the atmospheric density, the atmospheric winds, the ballistic coefficient, and the relative speed of the satellite within the atmosphere**.** Solar and geomagnetic storms produce variability that results in significant density uncertainty and mesoscale structure. Changing atmospheric composition also plays an important role. With the gradual cooling and contraction of the thermosphere due to increasing carbon dioxide, orbiting debris have longer lifetimes, and continue to accumulate. Understanding thermospheric density and composition changes is crucial and motivates the development of improved atmospheric density and wind models, especially during geomagnetic storm periods.

Typical estimates of the atmospheric density 1-sigma error at 400 km are on the order of 8-20%; yet this can grow by a factor of 2 – 4 during geomagnetic storm periods. These uncertainties become cumulative when trying to predict an object's future position. Atmospheric drag in LEO is highly dependent on the state of the neutral gas population that makes up the Earth's thermosphere region (80-1000 km altitude), especially its mass density and wind (speed and direction). Space weather events can alter the thermospheric state very quickly and produce variability that results in more than 4-sigma uncertainty in density. Furthermore, during storms, most of the geospace energy input to the atmosphere comes through the high latitudes and is associated with significant mesoscale structure. It can take several hours before the heating is globalized. The current understanding is that most of the energy input at high latitudes transfers to mid- and equatorial latitudes through waves, traveling atmospheric disturbances (TADs) and traveling ionospheric disturbances (TIDs). This contributes to variable drag for different satellites, depending on whether their orbit crosses the mesoscale heating region or not, especially during the main phase of geomagnetic storms. Constraining the errors in atmospheric density estimates is critical to improving atmospheric drag estimates, and over the long term, to improving the estimation of satellite orbits.

Although atmospheric drag decreases as a function of altitude, it still needs to be accounted for in the satellite orbit determination procedure. Current thermospheric models of neutral density need to be extended to exosphere heights to include predictions of densities at higher altitudes. Modeling the ion upflow/outflow is particularly important for predicting high altitude densities in the exosphere.

Overview of Science Goals:

The goal of this FST is to improve physics based models of thermospheric density, and via this to improve satellite drag estimation. Empirical thermospheric density models are commonly used by operational satellite tracking systems, since they have several advantages in terms of computational speed and frequently outperform physics-based models. A goal of this FST is to improve upon these empirical methods for both current epoch specification and prediction of neutral density through better physics-based modeling, including a better description of ion upflow and outflow regions, and through better utilization of data constraints, including with data assimilation techniques.

Applicability to NASA Heliophysics and LWS

This FST directly addresses several focus areas, including SSA- 2: Physics Based Satellite Drag Forecasting Capability. It also addresses the Decadal Survey's Key Science Goal 2: Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. It also address one of the risks identified by the White House Issues Strategies to Combat Growing Orbital Debris Risks: https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/ Societal Impact: https://www.wsj.com/articles/white-house-issues-new-strategies-to-combat-growing-orbital-debris-risks-1529332532

In addition, the FST addresses the Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI) Science Goals 1, 3 and 4:

AIMI Science Goal 1. Global Behavior of the Ionosphere-Thermosphere

> How does the IT system respond to, and regulate, magnetospheric forcing over global, regional, and local scales?
>
> AIMI Science Goal 3. Ionosphere-Thermosphere-Magnetosphere Coupling
> How do high-latitude electromagnetic energy and particle flows impact the geospace system? What are the origins of plasma and neutral populations within geospace?
>
> AIMI Science Goal 4: Plasma-Neutral Coupling in a Magnetic Field
> How do neutrals and plasma interact to produce multiscale structures in the AIM system?

Envisioned Focus Science Topic Implementation Strategy:

This effort requires a coordinated modelling and data assimilation effort to improve thermospheric models during storm and non-storm conditions. The FST also would benefit from close collaboration with the operational community who incorporate these models into orbit determination programs to calculate the atmospheric drag force. Improved thermospheric models are needed to estimate ion upflow/outflow regions and to provide better estimates of ionospheric variability. New data that could be incorporated into expanded models include observations from satellite sources such as DMSP, GOLD, ICON, GRACE, SWARM, TIMED-GUVI, TIMED-SABER, and ground based systems like ISRs and FPIs. Methods should be implemented to quantifiably test improvements in satellite drag estimation resulting from this FST.

Understanding and Predicting Radiation Belt Loss in the Coupled Magnetosphere

Introduction / Focused Science Topic Description:

The dynamics of the radiation belts is determined by an interaction of source, loss, and transport processes involving multiple particle populations. Trapped fluxes in the outer belt can vary by two orders of magnitude on timescales of a few hours to days, and the peak flux location is highly variable. The understanding of individual processes has been improved by the results of the Van Allen Probes mission, but our understanding of the dynamics of the radiation belts as a whole, and of the interaction between the different participating populations remains poor. This is especially true for understanding and predicting the loss of radiation belt fluxes in this dynamic system, be it during dropout events or through local wave-particle interactions.

There are two major loss processes that have been considered by the community. The first is non-adiabatic dropouts caused by magnetopause shadowing. This involves the loss of trapped particles on drift trajectories that intersect the magnetopause following sudden compressions of the magnetosphere. The second is wave-particle induced losses via pitch-angle scattering into the atmospheric loss cone caused by interactions between multiple co-located plasma populations such as the plasmasphere, the radiation belts, and the ring current. In addition, there is the possibility of other causes of radiation belt losses, such as rapid deceleration due to nonlinear wave-particle interactions.

This focused science topic addresses to what degree various processes are responsible for radiation belt loss.

Overview of Science Goals:

Compared to the energization of radiation belt particles and the study of radiation belt transport, the analysis, understanding, and prediction of the loss of radiation belt particles is farther behind. Therefore this FST concentrates specifically on improving our understanding of radiation belt loss processes within the framework of LWS needs. Studies to improve understanding of radiation belt transport or energization are not included in this FST. The two primary scientific goals of this FST are as follows: The first goal is to understand and predict how the overlap between plasma populations causes the loss of radiation belt electrons and controls the role of wave-particle interactions. The second goal is to understand and predict the radiation belt loss through non-adiabatic dropout events.

This FST intends to bring together observers and modelers who can make significant progress towards understanding and predicting radiation belt loss processes in the inner magnetosphere. A critical measure of success for this FST's investigations will be the demonstrated understanding and prediction of the temporal, spatial, and magnitude characteristics of relativistic electron loss, using observations and existing models covering the range from precipitation at tropospheric altitudes to processes in the radiation belts themselves. It is expected that appropriate metrics of uncertainty are provided with all investigations.

Applicability to NASA Heliophysics and LWS:

This FST addresses LWS Strategic Science Areas SSA-1 “Geomagnetic Variability”, and SSA-6 “Radiation Environment”. In addition, this FST addresses the 2013 Decadal Survey Key Science Goal 2 “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. ”

This FST also addresses the Decadal Survey Solar Wind-Magnetosphere Interactions (SWMI) Science Goal 4 “Establish how energetic particles are accelerated, transported, and lost,” the SWMI Science Goal 3 “Understand how plasmas interact within the magnetosphere and at its boundaries, ” and the SWMI Science Goal 1 “Determine how the global and mesoscale structures in the magnetosphere respond to variable solar wind forcing.”

Envisioned Focused Science Topic Implementation Strategy:

There are a number of recent observations (e.g., Van Allen Probes, Firebird, Barrel, ARASE, MMS, THEMIS) and historic ones (e.g., SAMPEX) that have greatly expanded the availability of the highest quality data on waves, in situ particles, and precipitating particles. Additional future data collections are on the horizon (e.g., GTOSat). At the same time, radiation belt models have now access to this unprecedented wealth of information against which their performance can be measured and improved. This FST encourages data analysis and modeling studies that focus on the loss of radiation belt electrons from the inner magnetosphere to atmospheric heights. Sample investigations could include: correlating wave and particle measurement to study in situ or magnetosphere-to-atmosphere relationships; quantifying electron loss with respect to the spatial overlap between radiation belts and plasmasphere and associated wave phenomena; and modeling non-adiabatic radiation belt drop-out events to understand the underlying physical processes.

In general, studies could include investigations that target a physical understanding of loss processes, improve our empirical understanding of the spatial and temporal characteristics of loss processes, or improve the predictability of relativistic electron loss and the presence (or absence) of conditions amenable to such loss.

Pathways of Cold Plasma through the Magnetosphere

Introduction / Focused Science Topic Description:

Low-energy plasma plays significant roles in the magnetospheric system. This plasma often dominates the number density and mass density of the magnetosphere. Consequently it alters the plasma waves that reside in the magnetosphere and thereby alters the wave coupling between other plasma populations: the ring current, the electron radiation belt, substorm-injected electrons, plasma-sheet ions, and plasma-sheet electrons. Low-energy magnetospheric plasma can also mass load dayside reconnection and alter solar wind/magnetosphere coupling.

Low-energy plasma in the magnetosphere takes the form of two very different plasmas: (1) the cold plasmasphere and its drainage plume and (2) the warm plasma cloak. The plasmasphere is well studied, although there are still important outstanding questions. The plasma cloak is less studied and is in need of basic surveys to establish its origin and evolution.

One outstanding question about the plasmasphere is the correctness of refilling rates in first-principles simulation codes. A coordinated effort is needed to (a) determine if and why the rates are wrong, (b) to add missing physics to the simulation codes, and (c) to get the correct ionospheric-outflow rates. In addition to the missing physics, corrections might involve better estimates of the neutral composition of the thermosphere.

The source of the plasma cloak has not been firmly established. The ionospheric-outflow mechanisms involved are not known and the magnetospheric and solar-wind parameters that control the outflow are unknown. Basic questions of the cloak's source concern where, when, and how much? Information about the evolution of the cloak plasma carried by magnetospheric convection, during active times and as activity ceases, is needed.

An outstanding issue for both the plasmasphere and the cloak is whether recirculation of the plasma into the magnetotail occurs and is important. Two possible pathways for the recirculation are (a) over the polar caps after the low-energy plasma enters the dayside reconnection outflow fan and (b) via the low-latitude boundary layer flow from the dayside into the magnetotail. Outstanding questions also exist on the dayside where these populations will interact with the magnetopause. Basic questions include understanding the spatial extent and density along the magnetopause boundary.

Overview of Science Goals:

This FST concerns the complex feedback between ionospheric outflows and magnetospheric plasma on the coupling of the solar wind to the system. The first goal of this FST is to establish a more accurate understanding of the physics involved in the refilling of the plasmasphere from the ionosphere, and to determine the ionospheric source of the warm plasma cloak and the factors controlling the source. A second goal of this FST is to establish a characterization of the evolution of the plasma cloak and an assessment of the impact that it has on the magnetospheric system. Finally, the third goal is to determine the existence and amount of recirculation of the low-energy plasmas from the dipolar region into the magnetotail and to assess the impact that any recirculation may have on the magnetospheric system.

Applicability to NASA Heliophysics and LWS:

The first LWS-program objective concerns the development of a predictive response of the magnetosphere-ionosphere-thermosphere system to solar wind driving. This FST concerns the complex feedback between low-energy magnetospheric plasma from the ionospheric outflows and the coupling of the solar wind to the system. This FST applies to three LWS SSAs: SSA-1 (Geomagnetic Variability), SSA-4 (Total Electron Content (TEC)), and SSA-6 (Radiation Environment).

This FST supports two Key Questions for Future Study in the 2013 Decadal Survey Consensus Report: "How are plasmas produced, lost, and energized in the magnetosphere?" and "How does the ionosphere-thermosphere system regulate the flow of solar energy throughout geospace?"

Envisioned Focused Science Topic Implementation Strategy:

This FST will involve coordinated research efforts between ionospheric, thermospheric, and magnetospheric researchers. The main focus is the complex feedback between magnetospheric plasma (from ionospheric outflows) and the coupling of the solar wind to the system. The strategies needed to achieve the first goal of this FST include: efforts to improve models utilizing first-principle plasmasphere-refilling simulation capabilities, and efforts to test these simulations with magnetospheric spacecraft observations. Obtaining the best experimental measures of refilling rates and the factors that govern the rates is part of these strategies. Plasma-physics and atmospheric-physics expertise will be involved as well as both theory and observation. Strategies needed to achieve the second goal of this FST include: surveys of low-altitude and equatorial spacecraft measurements from multiple missions in coordination with global magnetospheric modeling and machine learning to characterize the evolution of the plasma cloak. Strategies needed to achieve third goal are spacecraft observations of low-energy ions in the low-latitude boundary layer, high over the polar cap, in the mantle, and in the nightside plasma sheet to determine the ultimate fate of magnetospheric low-energy plasma after it reaches the dayside magnetopause.

Spacecraft observations of the refilling plasmasphere in the magnetosphere will be needed for the first goal. Spacecraft observations of the cloak in the magnetosphere and of ionospheric outflows from the ionosphere will be needed for the second goal. Spacecraft observations in the low-latitude boundary layer, over the polar cap, and in the magnetotail will be needed for the third goal. Potential missions involved are Van Allen Probes, THEMIS, FAST, POLAR, LANL, and Dynamics Explorer.

Understanding the Variability of the ITM System Due to Tides, Planetary Waves, Gravity Waves, and Traveling Ionospheric Disturbances

Introduction/Focused Science Topic Description:

Variability in the Ionosphere-Thermosphere-Mesosphere (ITM) domain consists of global and regional variations that can modify physics and ion-neutral chemistry on a variety of time-scales. Variability can be introduced by tides, planetary waves (PWs), and by gravity waves (GWs) / traveling ionospheric disturbances (TIDs). It is now widely accepted that the lower atmospheric forcing of tides, PWs, GWs, and the middle atmosphere propagation environment of these waves provide the bottom-side control for dynamics, transport and mixing in the neutral atmosphere on time scales from minutes to several days. Significant difficulties in forecasting these variations arise from ITM variability associated with these waves, and their interactions with each other and with the background flow and turbulent eddies. While the importance of wave forcing from below is without dispute, major challenges remain in understanding the spatio-temporal evolution of the wave spectrum in the neutral atmospheric system, including wave-wave and wave--mean-flow interactions that excite additional motions and drive variability, structure, mixing, composition and energy balance. For example, gravity wave activity is modulated by interactions with other waves and tides and therefore realistic modeling of the wave activity requires inclusion of the tides (and vice versa).

These waves generate significant ionospheric disturbances. For example, TIDs are a major source of total electron content (TEC) variability, with classification ranges (large-scale, medium-scale) that have different source characteristics not yet fully understood. Medium-scale TIDs (MSTIDs) and some large-scale TIDs (LSTIDs) have clear relations to gravity wave drivers. Some MSTIDs have been associated with gravity waves that ultimately have meteorological sources including tropospheric events. However, other TID features that are important sources of ionospheric variability do not appear to be associated with neutral atmospheric drivers. For example, high latitude LSTIDs often have auroral sources while other LSTIDs can be generated by the terminator. LSTIDs can have large amplitudes of up to 20% of background TEC, with horizontal velocities of 300-750 m/s, 1000-3000 km wavelengths, and 1-2+ hour wave periods. Generally, studies of TID launch timing, propagation properties, source mechanism(s), and other related properties are still needed in order to improve modeling and prediction of ionospheric variability.

Overview of Science Goals:

The primary scientific goal of this FST is to improve prediction capability for the variability in the ITM region due to spatio-temporal quasi-periodic phenomena. To achieve this, a better physical understanding of the process of lower-upper atmosphere coupling via tides, PWs and GWs is needed as well as a better wave morphology in the ITM region as a whole. This includes a better understanding of the generation and morphology of traveling ionospheric disturbances within the ionosphere.

Applicability to NASA Heliophysics and LWS;

This research will benefit the space weather community, and the ionospheric and atmospheric research community, including improved models.

The topic is fundamentally important for understanding ionosphere density structure and energy transport in the M-I-T coupling system across latitudes. This topic will increase physics-based understanding that will significantly improve forecasting for SSA-4 (Total Electron Content) and SSA-5 (Ionospheric Scintillation). This will occur by connecting the sources of TIDs to wave-driven variability of the ionosphere-thermosphere system on time scales ranging from minutes to hours. Understanding of this intrinsic I-T variability is at the forefront of LWS-TRT research.

The goal is to derive a model, or coupled set of models, that enable specification of the global ITM system and its variability.

Envisioned Focus Science Topic Implementation Strategy:

To improve understanding of neutral atmosphere variability the following will be studied: (1) seasonal, intra-annual and interannual variations in semidiurnal tides in the lower thermosphere and their imprint in the ionosphere-thermosphere system; (2) mechanisms driving the lunar tidal variability, and the short-term variability in diurnal and semidiurnal tides, as well as the variability modes related to tide-tide and PW-tide interactions; and (3) connections between stratospheric planetary wave activity and PW variations in the ITM system. Strategies to study these phenomena include: investigations that combine modelling and observations to understand coupling and responses in the atmosphere - ionosphere - magnetosphere; coupled climate circulation models providing regional scales, wave-scale models, and plasma models that generate ionospheric signatures; mechanistic gravity wave models that can be nested in larger-scale models that resolve tides and planetary waves.

Alongside long-term GUVI observations from the NASA TIMED satellite, the upcoming ICON and GOLD missions will provide important new data for this topic. Other space-based ionospheric and thermospheric data are also available from such sources as DMSP, DEMETER, TIMED/GUVI, COSMIC, SWARM, Arase, GOCE, CHAMP, and the upcoming COSMIC-2 mission. These data can be utilized to verify models and to help build predictive capabilities.

To improve understanding of TIDs within the ionosphere, the following studies are envisioned: studies of TID morphology during geospace storm and non-storm time periods; studies which examine TID "launch" timing, propagation, source mechanism(s), and other properties, such as the frequency and importance of multiple TID/GW interactions; studies aimed at identifying the relationship between TIDs and the generation of irregularities leading to radio-wave scintillation.

These ionospheric studies will benefit from global ground-based GNSS TEC data as well as the ground based networks of magnetometers, ionosondes, and airglow-based neutral wind and all-sky emissions data are available as well. The SuperMAG and AUTUMN ground-based networks as well as space-based observations from AMPERE now have significantly increased measurement densities for determination of ionospheric currents.

The Variable Radiation Environment in the Dynamical Solar and Heliospheric System

Introduction / Focused Science Topic Description:

Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) propagate in the heliosphere, forming the radiation environment close to Earth and elsewhere in the interplanetary space. Because of the low plasma density of the interplanetary medium, the dynamics of energetic particles is primarily influenced by electric and magnetic fields. GCRs and SEPs constitute a major threat to satellites and astronauts in space. This danger is difficult to mitigate by current technology.

The energetic particle radiation varies at different temporal and spatial scales. The high-energy component of energetic charged particles (>500 MeV) at Earth is registered by ground based neutron monitors. The deep solar minimum in cycle 23 and relatively weak cycle 24 have led to record increases in the flux of Galactic Cosmic Rays (GCRs). Based on Voyager 1's in situ measurement of GCRs in the interstellar medium, 75% of the cosmic rays with energies ~1 GeV are filtered out by the heliosphere. Incoming cosmic ray flux is affected by a variety of physical processes internal to our heliosphere. The recent changes in the solar wind associated with the recent weak solar cycles have provided important clues of underlying physics. If the solar activity descends into a Dalton minimum condition, the level of the GCR flux will surge and needs to be quantitatively determined. The radiation environment is variable also because of solar transient events like solar flares and coronal mass ejections. The most extreme SEP acceleration gives rise to ground level enhancement events with an increase of energetic particle flux at hundreds of MeV. Fast coronal mass ejections (CMEs) lead to decreases of the high-energy particle flux for days known as the Forbush decrease. These activities are known to be observable in the whole heliosphere. A primary goal of the upcoming Interstellar Mapping and Acceleration Probe (IMAP) mission will be connecting energetic particles measured at 1 AU with those over the whole heliosphere. It is important to monitor and understand the variability of energetic particle radiation in the dynamical changing solar corona and heliosphere.

This study is timely with Interstellar Boundary EXplorer (IBEX)'s increasingly detailed measurements of the dynamical heliosphere and its boundaries, and the upcoming IMAP mission, which offer unprecedented measurements of energetic particles throughout the heliosphere. Work done under this topic will provide additional insights on the coupling between Earth's space environment and its interstellar surroundings. Such studies will also impact the data-limited study of astrospheres, a timely topic given increased emphasis on Sun-As-a-Star investigations in the era of Kepler, Transiting Exoplanet Survey Satellite (TESS), and James Webb Space Telescope (JWST).

Overview of Science Goals:

The specific goals of this FST are: 1. to determine the influence of solar and heliospheric plasma dynamics on high-energy particle radiation environments within the heliosphere and 2. To determine the influence of major solar eruption events on the high energy radiation environment near Earth and interplanetary space. In addition, this FST has the goals of improving the numerical models of cosmic ray modulation in the heliosphere, high-energy particles from major solar eruptions, and the Forbush decrease by extreme CME events.

Applicability to NASA Heliophysics and LWS:

The FST addresses directly the SSA-0, SSA-3, and SSA-6. It also addresses Decadal Survey goals: Determine the origins of the Sun's activity and predict the variations in the space environment; Determine the interaction of the Sun with the Solar System and the interstellar medium; Discover and characterize fundamental processes that occur both within the heliosphere and throughout the Universe.

Envisioned Focused Science Topic Implementation Strategy:

This FST has the goal of improving the numerical modeling of cosmic ray modulation in the heliosphere and of the Forbush decrease. Available data sources for this FST include spacecraft data for solar wind parameters at 1 AU, IBEX, data for highly energetic particles such as ACE, GOES, Voyager, AMS-02 and Neutron Monitor data.

Types of investigations to address this FST's science goals include studying the effect of variations in solar wind dynamic pressure on the cosmic ray flux change; performing correlation analyses between neutron monitor data and spacecraft data to understand change of high-energy charged particles such as Forbush decrease; studying the influence of major solar eruption events on the high energy radiation environment near Earth and interplanetary space; and performing analysis of temporal and spectral properties of large SEP events and simulations of high-energy particle dynamics and comparison with spacecraft measurements

The Origin and Consequences of Suprathermal Particles that Seed Solar Energetic Particles

Introduction / Focused Science Topic Description:

Understanding and forecasting Solar Energetic Particles (SEPs) is an essential component of the LWS program. To achieve that, substantial improvements are needed in our understanding of SEP sources and acceleration processes. Suprathermal ions (ions of a few times the solar wind thermal particle energy up to hundreds of keV per nucleon) are known to play a significant role as the seed population in the acceleration of high energy particles by coronal mass ejection (CME) shocks. The SEPs measured at Earth's orbit are highly variable in their intensity-time profiles, spectrum shape, and charge-to-mass ratio dependence due to mingled effects from seed particle acceleration and injection, shock acceleration and SEP transport. In the quest for a reliable prediction of the properties of large SEP events, it is necessary to understand the sources of variability from each of those processes. Predicting these variations demands refreshed observations and theories for seed suprathermal ions and their effects in producing the variability in SEP events. This requires a collaborative team effort between observers, modellers, and theorists suitable for an LWS-TR&T focused science topic.

The community has not yet reached a consensus on the source and acceleration mechanisms of suprathermal particles, and how exactly the seed particles contribute to large SEP events. The suprathermal particles contributed to the largest SEP events must be produced close to the Sun, and their production process is likely smeared due to mixing, transport, and other effects by the time that they are observed at the Earth's orbit. The newly launched Parker Solar Probe will fill this gap by providing in-situ energetic particle measurements close to the Sun. This focused science topic would help with interpreting these data and could also help pave the way for defining science requirements for future suprathermal-particle-focused instrumentation.

Overview of Science Goals:

The goal of this FST is to understand the origin of suprathermal particles and their effects in producing temporal and spatial variations and different spectral properties of SEPs. To address this goal, projects should aim to understand the relative roles of solar flares and CMEs in producing large SEP events; to investigate particle acceleration mechanisms for producing suprathermal particles at the Sun and in the heliosphere; and to prepare for analysis of suprathermal particle observations from upcoming missions such as the Parker Solar Probe, Solar Orbiter, STPSat-6, and IMAP. The outcome from this FST will advance our understanding of variations in large SEP events.

Applicability to NASA Heliophysics and LWS:

This topic is relevant to SSA-0, SSA-3, SSA-6, and addresses the Decadal Survey goals: Determine the origins of the Sun's activity and predict the variations in the space environment; Determine the interaction of the Sun with the Solar System and the interstellar medium; and Discover and characterize fundamental processes that occur both within the heliosphere and throughout the Universe.

Envisioned Focused Science Topic Implementation Strategy:

Theoretical and observational researchers need to work together in this FST. Modeling methods appropriate for addressing this topic include realistic flare and CME models as well as particle acceleration and transport models including suprathermal particles and large scale shock acceleration. Observation methods appropriate for addressing this topic include in-situ spacecraft measurement of low energy suprathermal particles and high-energy SEPs with different species, as well as remote sensing observation of seed particles in their source regions.

Connecting Thermospheric Composition and Space Weather

Introduction/Focused Science Topic Description:

Both quiet time and storm time geomagnetic processes yield changes in thermospheric composition due to changes in the circulation (atomic oxygen to molecular nitrogen, O/N_2) and direct changes in composition (nitric oxide, NO). Several of these changes are listed here. First, changes in thermospheric O/N_2 change the thermospheric density and the total electron content (TEC). Second, changes in thermospheric NO result in both changes in the radiative balance and composition. NO emits IR radiation (5.3 micron) which cools the thermosphere and speeds up the recovery of the thermosphere. NO can also destroy ozone (O_3) through catalytic cycles. The impact of thermospheric NO on the ozone layer is then determined by the subsequent transport of NO from the thermosphere into the mesosphere and stratosphere by meteorological processes. This meteorology includes transport associated with the wave-driven circulation at high latitudes and the polar vortex. The impact of repeated geomagnetic storms can be used to assess the impact of space weather events on the ozone layer and possible impacts on the climate over longer time scales.

NO cooling competes with storm time thermospheric heating, resulting in a thermostat effect. Excess NO emissions can arrest thermospheric expansion by cooling the thermosphere during intense storms. The strongest events curtail the interval of neutral density increase and produce a phenomenon known as thermospheric "overcooling." The neutral composition of the thermosphere also affects plasmaspheric refilling rates from the ionosphere.

These changes highlight coupling between the magnetosphere and the thermosphere, mesosphere and stratosphere. The response of O/N_2 and NO to geomagnetic activity driven by Coronal Mass Ejection (CME) and high-speed stream Co-rotating Interaction Region (CIR) is unresolved. Both the direct changes in the thermospheric density and the density changes due to radiative cooling impact satellite drag. Compositional changes also impact the presence and evolution of ionospheric storm enhanced density (SED) as well as possible ion-neutral-interaction-driven changes in convection.

Overview of Science Goals:

This FST addresses the coupling between space weather and atmospheric composition in terms of how changes in neutral composition influence space weather and vice versa.

Progress will require coupled dynamical-chemical modeling of the middle and upper atmosphere. This investigation will improve the forecasting capabilities of current and future computational models. Comparisons of models to satellite and ground-based data is critical in evaluating the success of these models. The proposed research will lead to improvement in space weather modeling and prediction, and will benefit both the atmospheric research and operational satellite tracking community with its improvement in atmospheric drag models.

These user communities have been identified: Space Weather (GEM, CEDAR), Ozone (NOAA, NASA), COSPAR, Satellite Drag and Orbit (AF, NOAA)

Applicability to NASA Heliophysics and LWS:

This FST topic addresses the following SSAs: SSA-1: Geomagnetic Variability, SSA-2: Satellite Drag, and SSA-4: Total Electron Content (TEC)

It addresses the key science goals 2, 3, 4 listed below and identified in the National Academies overview: Relevance to Solar and Space Physics: A Science for a Technological Society.

Key Science Goal 2. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.
Key Science Goal 3. Determine the interaction of the Sun with the solar system and the interstellar medium.
Key Science Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Finally it addresses the following Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI) Decadal science goals:
AIMI Science Goal 1. Global Behavior of the Ionosphere-Thermosphere
How does the IT system respond to, and regulate, magnetospheric forcing over global, regional, and local scales?
AIMI Science Goal 2. Meteorological Driving of the IT System
How does lower-atmosphere variability affect geospace?
AIMI Science Goal 3. Ionosphere-Thermosphere-Magnetosphere Coupling
How do high-latitude electromagnetic energy and particle flows impact the geospace system?
What are the origins of plasma and neutral populations within geospace?
AIMI Science Goal 4. Plasma-Neutral Coupling in a Magnetic Field
How do neutrals and plasmas interact to produce multiscale structures in the AIM system?
AIMI Science Goal 5. Planetary Change
How is our planetary environment changing over multidecadal scales, and what are the underlying causes?

Envisioned Focused Science Topic Implementation Strategy;

It is envisioned that a combination of modelling and observations will be required to address this FST goal of improved understanding of the coupling and responses of neutral dynamics and space weather in the atmosphere-ionosphere-magnetosphere. In particular, this will require: the development of models and validation of simulations that can accurately represent O/N_2 and NO in response to quiescent and active geomagnetic conditions; studies which compare modeled O/N_2 and NO with existing observations; studies to understand the coupled response under a variety of geomagnetic activity (both quiet and active); assessments of the total effect of changes in both O/N_2 and NO on the composition of the atmosphere and the impact of space weather on the thermosphere; developments of data-model synthesis techniques to improve the representation of physical processes in the models.

Data for incorporation into models or model validation for this FST is available from several satellite programs. Important magnetospheric drivers are available from the Cluster, SAMPEX, THEMIS, Van Allen Probes, Arase, MMS. The following NASA satellites provide currently provide or will provide measurements of O/N_2: GOLD, ICON, TIMED/GUVI provide measurements of O/N_2. TIMED/GUVI and TIMED/SABER provide simultaneous measurements of NO and 5.3 micron emission respectively. The DMSP constellation provides measurements of particle precipitation.

Understanding Ionospheric Conductivity and Its Variability

Introduction / Focused Science Topic Description:

The ionospheric conductivity tensor is a derived quantity that is central to coupling between the solar wind and the magnetosphere, ionosphere, and thermosphere. Conductivity variations in the ionosphere provide an important electrodynamic boundary that varies significantly due to many factors, such as normal sunlight/darkness variations, neutral atmospheric changes, and the presence of auroral precipitation. Most first-principles numerical models have embedded electrodynamics equations that require knowledge of the distribution of conductivities and their variations to properly interpret the tightly coupled feedback loops between the ionosphere and magnetosphere.

However, the ionospheric conductivity and its variability are in general not well understood. Horizontal conductivity structure can depend on dynamic processes such as auroral substorms and high-latitude convection, ionospheric disturbances, and large scale plasma transport. The vertical structure of the conductivity is widely ignored by global models and yet is critical for mesoscale energy deposition to the high latitude ionosphere and thermosphere. Developing realistic models for ionospheric conductivity will address this gap and lead to improved predictive models of whole atmosphere variations associated with geomagnetic activity.

This is a timely topic for two reasons:
(1) predictive space weather modeling has advanced sufficiently to make it feasible to compute the global modeled distribution of the ionospheric conductivities in near-real time;

(2) large data resources exist that allow for detailed model-data comparisons at a level not previously possible.

Overview of Science Goals:

The science goals of this FST are the development of realistic ionospheric conductivities for use in first principles models. In particular, efforts should focus on conductivity variations driven by vertical structuring; energetic auroral electron and ion precipitation; dynamical processes at high latitudes; and traveling ionospheric disturbances. An additional goal of this FST is to assess to what degree each of the above parameters affect overall magnetosphere-ionosphere coupling during geomagnetic activity. The communities that will most directly benefit from these activities include the GEM and CEDAR programs, but ultimately the entire space science community will benefit.

Applicability to NASA Heliophysics and LWS:

The magnetosphere-ionosphere interactions that this topic addresses are the primary driver of global ionospheric storms that have a major impact on both satellite drag (SSA-2) and total electron content (SSA-4). There is also a direct effect on ionospheric scintillation at low, middle and high latitudes, particularly during severe storms (SSA-5).

This FST also addresses Decadal Survey Key Science Goal 2: "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs", and Decadal Science Challenge "Solar Wind-Magnetosphere Interactions (SWMI) - 3: Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind".

Envisioned Focused Science Topic Implementation Strategy:

Data analysis studies should be coordinated with theoretical and numerical modeling studies, especially for assessing the effect of realistic conductivity on global magnetospheric models. Data implementation strategies may consist of conductivity-focused analysis of space-borne datasets (e.g.: GOLD, ICON, COSMIC-2, GNSS, CHAMP, DMSP/GUVI, SUSSI, AMPERE) coupled with datasets from ground based facilities such as Incoherent Scatter Radars (ISR), SuperDARN, and SuperMAG. Note that joint analysis methods may be required since some of these assets provide important but indirect system scale information (e.g., integrated ionospheric density distributions from GNSS total electron content).

Potential example studies include: development of methods, including assimilative ones, that combine some or all of the observational assets in order to produce 3D conductivities at different latitudes; modeling investigations of the effects of precipitation on the 3D conductivity structure and the feedback on the magnetosphere; modeling investigations of ionospheric processes (e.g., turbulence) producing conductivity variations beyond those driven by solar ionization and precipitation; quantification of feedback pathways between ionosphere and magnetosphere that structure conductivity; investigations of conductivity variability due to plasma convection (e.g., patches), and its feedback on the magnetosphere; investigations exploring the coupling of high- and mid-latitude conductivities (auroral) to low-latitude ones (equatorial), under conditions of strong geomagnetic activity.

Modeling and Validation of Ionospheric Irregularities and Scintillations

Introduction / Focused Science Topic Description:

Ionospheric scintillations are rapid fluctuations in a received radio signal's amplitude, phase and angle of arrival. They are a result of trans-ionospheric passage of the signal undergoing refractive and diffractive interference through an irregular medium (the plasma of the ionosphere) acting effectively as a diffraction grating. Scintillation is observed to occur at a range of wavelengths. L-Band scintillation adversely impacts the continuous tracking of Global Navigation Satellite System (GNSS) signals for position, navigation, and timing services. At UHF and lower frequencies, scintillation leads to intermittent communications outages, sometimes with serious impacts [Kelly et al., 2014].

Low- and high-geomagnetic latitudes are typically the zones where scintillation is most frequent and severe. The structure, orientation, and conditions leading to the irregularities that cause scintillation differ as a function of latitude. A prediction capability is needed at low latitudes that involves specifying the ambient ionospheric and thermospheric weather conditions including electrodynamics and wind, as well as the gradient of bottomside electron density and rising of the ionospheric F layer. At high-latitudes, a prediction capability is needed that considers a host of instability mechanisms that drive severe plasma density, temperature and velocity irregularities imbedded in a time-dependent magnetic field. Achieving these capabilities will require observational and modeling investigations of the conditions, mechanisms and processes leading to the formation of ionospheric irregularities, as well as the dynamics driving their evolution and the impact on radio signals passing through them.

The upcoming availability of ICON and GOLD observations make this the perfect time to launch investigations of scintillation in the vicinity of the equatorial ionization anomaly. Early indications are that a low-to-mid latitude mesosphere-lower-thermosphere (MLT) driven phenomenon (the annual/semiannual asymmetry, e.g. Mendillo et al. [2005], Qian et al. [2013]) may play an important role in the presence of low latitude scintillation. These new missions will allow us, for the first time, to determine how low-to-middle latitude MLT processes govern the plasma supply and state of the low-latitude thermosphere and ionosphere at the time of spread-F onset.

At the same time, the growth of the number of high-latitude polar flights and the opening of the Arctic to shipping traffic has increased the need for better specification and prediction of the polar ionosphere and RF system impacts. It is anticipated that the demand for communications, navigation and surveillance systems in the higher latitude regions will only continue to grow.

Overview of Science Goals:

The Goal of this FST is to understand and model the conditions that lead to the onset and evolution of ionospheric irregularities and resulting scintillation events. Further advances in understanding the initiation and evolution of these irregularities are needed at low, mid and high latitudes. Specific goals are to: identify the mechanisms that are responsible for ionospheric irregularities and scintillations in the zone selected (low latitude, mid-latitude, high latitude); determine what they tell us about their growth rates and spectral characteristics; identify the relationship between scintillation at one frequency and the likelihood of scintillation at other frequencies; identify the dominant instability mechanisms responsible for polar F-region irregularities; develop models of the ionosphere parameterized by space weather drivers that can seed physics-based modelling efforts and reproduce observations; quantify a relationship between the longitudinal structure and scintillation effects, and the dynamics, persistence and spatial scales of instabilities after they grow.

A measure of success for investigations through this FST will be the demonstrated comparison of the temporal, spatial, and magnitude variability in ionospheric scintillation using observations and new or existing models. Appropriate metrics of uncertainty would quantify improvements that are beyond current community capabilities. As an example, a number of empirical methods such as statistical and machine-learning approaches can be used to uncover dominant parameters and processes and guide modeling efforts. Numerical simulations should include estimates of uncertainty via methods such as ensemble modeling. Simulation results should be compared with pertinent observations to quantify both success level and the gaps in understanding.

Applicability to NASA Heliophysics and LWS:

Geomagnetic variability Science Area SSA-1: At high latitudes, the processes responsible for the development of F region irregularities that are often manifested as scintillation in trans-ionospheric radio propagation need to be understood for the phenomenon to be predicted. Potential links between occurrence rates and global-scale waves in the MLT indicate significant advances in both short- and long-term predictability are achievable. Total Electron Content Science Area SSA-3: Currently the best tool for observing high latitude irregularities is the GNSS network measuring total electron content, which shows frequent and obvious signatures of polar cap patches and equatorial plasma depletion . The corollary is that formation of these irregularities are processes that needs to be included in global-scale models of TEC. Ionospheric scintillation research and modeling are central to the LWS Physics-based Scintillation Forecasting Capability Science Area SSA-5: Spread F is a macroscale phenomenon with well-known and documented links to scintillation, e.g. Tsunoda [1988]. Intense density irregularities form especially at the edges of F-region enhancements and cause scintillation on transionospheric signals, as well as scatter of HF transmissions. Its occurrence dramatically reconfigures the high-latitude ionosphere over periods of a few hours. Solar wind variability is the ultimate driver of this phenomenon, so its predictability at the one-hour level may be seen as within reach.

This FST is relevant to Decadal Survey Key Science Goal 2: "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere,and atmosphere and their response to solar and terrestrial inputs."

Envisioned Focused Science Topic Implementation Strategy:

An improved theoretical understanding of the initiation and evolution of ionospheric irregularities resulting in scintillation is critical to enabling a physics-based scintillation forecasting capability. A number of approaches are appropriate, for example: investigations of polar cap patches or "blobs" due to enhanced particle precipitation, and the instabilities leading to the irregularities associated with these; interhemispheric studies of high-latitude scintillationinducing irregularities in the polar cap; kinetic or PIC models of instabilities and raypath propagation through them; a strong consideration of relevant geometries and scale sizes; explorations of the seeding mechanisms by which the instabilities initiate and evolve; the demonstration of these effects; and comparisons with observed scintillation data; simulations of the structure of low and equatorial latitudes of plasma density and plasma drifts; simulations of high latitude plasma structures; simulations of vertical plasma motions; quantification and simulation of the effect of energy transport (TIDs/TADs) longitudinal structure; quantification of a relationship between the longitudinal structure and scintillation effects; determination of whether seeding is required for the instability to grow; determination of the dynamics or persistence time and spatial scales of the instability after it grows; quantifying improvements through model validation with appropriate metrics.

Fast Reconnection Onset

Introduction / Focused Science Topic Description:

Magnetic reconnection is one of the most fundamental physical processes in Heliophysics and in Space Science more broadly. Reconnection spans across energy scales, from nanoflares that contribute to coronal heating to solar flares which are the largest explosions in the solar system. It is the mechanism by which stored magnetic energy is suddenly converted into kinetic and thermal energy, radiation, and accelerated particles and is therefore a fundamental source of the most energetic space weather phenomena, including coronal mass ejections and geomagnetic storms. Although ubiquitous, reconnection is a process that requires critical conditions to be fulfilled in order to occur, making it an excellent probe of magnetic field topology and dynamics throughout the heliosphere. For the Living with a Star program, outstanding questions are: When, where, and how does reconnection commence? When reconnection has commenced, what is the reconnection rate, and in particular, what are the criteria for fast reconnection to occur in various physical environments within the heliosphere? This Focused Science Topic aims to address these questions, targeting the onset of fast reconnection.

One criterion for fast magnetic-field-line reconnection to occur is that a current sheet must thin to a critical width. As examples, many fast reconnection investigations in the collisionless regime require that ions and/or electrons become demagnetized to allow the magnetic field to slip through the collisionless plasma. Another commonly invoked criterion requires the excitation of the tearing instability, which in turn relies on the current sheet reaching a critical aspect ratio. In partially-ionized collisional plasmas, reconnection studies have shown that fast reconnection is achievable if the ion-electron recombination rate exceeds a critical threshold, and that this can also be related to the current sheet thinning down below the ion-neutral coupling scale. Thinning of current sheets may be caused by, for example, (nonuniform) compression of the plasma, shocking of the plasma, and stressing the large-scale magnetic configuration in which the current sheet is imbedded. The critical thickness for fast reconnection onset has been related to ion gyro-radii, to ion inertial lengths, to electron gyro-radii, to ion-neutral coupling scales, and to tearing mode criteria. The criteria for the onset of fast reconnection may depend on such variables as the amount of magnetic shear, the amount of velocity shear, ion composition, ion plasma beta, or plasma asymmetry across the current sheet.

Throughout the heliosphere, numerous observations are now available of current-sheet conditions related to the onset of reconnection: it has been observed via remote imaging in the onset and evolution of coronal mass ejections and flares and for the evolution of coronal helmet streamers; it has been observed via in-situ measurements for the heliospheric current sheet, for solar-wind directional discontinuities, for the Earth's magnetosheath, for solar-wind/magnetosphere coupling at the dayside magnetopause, and for substorms in the Earth's magnetotail.

Overview of science goals.

Establish an understanding of what the critical conditions are for the onset of fast reconnection at a current sheet in the various regimes relevant for heliophysics. Determine what the onset criterion and reconnection speed depends on for these various regimes.

Investigate the global and local-scale processes which bring current sheet to the critical state required for reconnection for the various reconnection phenomena active in the solar corona, solar wind, and the Earth's magnetosphere.

Establish predictive parameters for the onset of reconnection that can be implemented in large-scale MHD simulation codes for the corona, solar wind, and the Earth's magnetosphere.

Applicability to NASA Heliophysics and LWS:

Due to its prevalence, magnetic reconnection studies directly address several key Strategic Science Areas (SSAs), including SSA-0 (Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth's atmosphere), SSA-1 (Geomagnetic Variability), SSA-3 (Solar Energetic Particles), and SSA-6 (Radiation Environment). However, due to the role of reconnection in coronal heating and irradiance, this topic is ultimately relevant to all LWS SSAs 0-6.

The inherent cross-disciplinary nature of this Focused Science Topic and its direct correspondence with space weather as a driver of energy release is ideally suited for the LWS program.

This FST, by addressing reconnection onset throughout the heliosphere, will address key aspects of the Decadal Survey key questions: "What is the role of magnetic reconnection in energy release in coronal mass ejections and flares?" "What are the interactions and feedbacks that connect the magnetosphere, solar wind, and ionosphere?" and "How does the Sun's magnetic field shape the dynamic heliosphere?"

Envisioned Focused Science Topic Implementation Strategy:

Theory and simulation studies of reconnection onset criteria for plasma regimes and magnetic field configurations relevant to heliophysics, including particle in cell, hybrid, multi-fluid magnetohydrodynamic, and Hall magnetohydrodynamic investigations; remote sensing studies of current sheet evolution and reconnection onset in the solar corona, heliosphere, and laboratory experiments; in situ studies of current sheet evolution and reconnection onset in the outer corona, solar wind, magnetosphere, and laboratory experiments; theory and modeling studies of global and local phenomena which bring current sheets into fast reconnection states" in magnetic field configurations important for heliophysics phenomena, including both kinetic physics and global magnetohydrodynamic investigations; statistical analysis of observed reconnection events and detailed analysis of prime reconnection events; development of predictive parameters for implementation into large-scale magnetohydrodynamic simulations of heliophysics reconnection phenomena.

Extreme Solar Events --- Probabilistic Forecasting and Physical Understanding

Introduction / Focused Science Topic Description:

Extreme solar events introduce significant potential hazards associated with abrupt increases in solar energetic particle radiation and geospace superstorms. Rarely occurring extreme solar events generate X-rays and solar radio bursts, accelerate solar energetic particles to relativistic velocities within minutes and cause powerful coronal mass ejections. At Earth, the associated changes in the space environment can cause detrimental effects to the electricity grid. In space, extreme solar events can damage satellites and avionics and pose a hazard to space travellers. Extreme solar events also cause increases in radiation levels at aviation altitudes that can affect airline passengers and crews. Additional effects of extreme events include disruptions of satellite navigation systems, mobile telephones, and a host of additional effects for Earth (including ozone destruction) and satellite-based technologies. Extreme solar events have consequently been identified as a risk to the world economy and society.

Several examples of extreme solar event effects include the 1989 collapse of part of the Canadian
electricity grid. A superstorm which occurred in 1859, now referred to as the 'Carrington event' is the largest for which we have measurements; and even in this case the measurements are limited to perturbations of the geomagnetic field. An event in 1956 is the highest recorded for atmospheric radiation. The events of August 1972, October 1989 and October 2003 were associated with the highest recorded levels of solar energetic particle radiation measured on spacecraft. How often solar superstorms occur, what their probabilities are, how they are generated, and whether the events listed above are representative of the long term risk are not known. The general consensus is that a solar superstorm is inevitable, a matter not of 'if' but 'when.' This FST calls for a concerted effort to study extreme solar events observationally, theoretically and using simulations to identify: potential causes, and possible precursors of these events with an emphasis on development of the physical understanding that may be used for probabilistic forecasting. Since extreme solar events are rare, studies of moderate to large storm events will be important for developing the physical understanding necessary for predicting the behavior of extreme events.

Overview of Science Goals:

The goals of this FST are twofold: to develop models of extreme solar events, and to test these models via comparison against remote sensing satellite data of moderate to large solar events and historic extreme solar event data from sources such as ice cores and tree rings. Measures of success are: the development of metrics to test or quantify the success of extreme solar event models; the development of observational precursors that can be used to quantify potential development of extreme solar events; the development of methodologies for probabilistic forecasting of extreme solar events; the examination of historic datasets that can be used to assess extreme events that may have occurred in the past.

The driving motivation of this FST is to advance substantially our physical understanding of extreme solar events, to identify observational precursors, and to develop an understanding of the probabilities that such events will arise in the future. Proposals to this FST should demonstrate how the expected advances will be relevant to user needs (for example, NASA/SRAG or NOAA/SWPC). Individual proposals should identify how they will contribute to the FST and aid with development to enable predictive understanding, observationally based forecasting and probabilistic understanding. Proposed investigations should outline their methodologies for enabling these goals, and the data sources and metrics to be used to monitor their progress. Successful investigation teams are expected to provide, with their annual reports, a description of their progress towards one or multiple goals (enable predictive understanding, observationally based forecasting, and probabilistic understanding) .

Applicability to NASA Heliophysics and LWS:

This FST directly addresses Strategic Science Area SSA-0, which focuses on physics-based understanding enabling forecast capabilities for the events driven by the variability of solar magnetic fields. This FST also addresses SSA1-6, as those strategic science areas all rely in some way on the development of predictive understanding emerging from SSA-0.

This FST addresses Decadal Survey Key Science Goal 1: “Determine the origins of the Sun’s activity and predict the variations in the space environment,” by investigating the origins of extreme solar events. In addition, it addresses Decadal Science Challenge “Sun-and-Heliosphere-3: Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere,” by studying the storage and explosive release of energy in extreme solar events.

Envisioned Focused Science Topic Implementation Strategy:

The envisioned implementation strategy is to combine a number of methods and efforts to develop models of extreme events and test them against extreme event data. In particular, this would involve: studies that use historical records (ice core 10Be and 36Cl data, 14C in tree rings) and spacecraft data to identify extreme events for comparison with results of models; numerical models to understand physical origins of extreme solar events and identify potential observational precursors that may be used in the future for event forecasts; application of statistical methods for probabilistic forecasting based on specific observational precursors; models of the solar origin of large eruptions, and evolution of coronal mass ejections through the heliosphere that leads to strong southward IMF and highly geoeffective events .

Connecting Auroral Phenomena with Magnetospheric Phenomena

Introduction / Focused Science Topic Description:

It has been a longstanding aspiration to use images of the aurora to interpret the corresponding dynamics in the nightside magnetosphere and magnetotail. Two issues stand in the way of realizing that powerful capability: (1) uncertainty in the mapping of the magnetic connection between the ionosphere and the magnetosphere and (2) not knowing what processes in the magnetosphere produce the various types of aurora.

The aurora represents a significant transformation of energy in the nightside magnetosphere that drives currents, energizes particles, ionizes the thermosphere, heats the ionosphere, removes particles from the magnetosphere, and drives ionospheric outflows. In addition to removing energy from the magnetosphere, aurorae alter the entropy of magnetospheric flux tubes. Aurora are ultimately driven by the solar wind driving of the magnetospheric convection and the loading of magnetic flux into the magnetotail. Some types of aurora are associated with increasing levels of magnetospheric convection, some with the aftermath of substorms; some types of aurora seem to be related to magnetospheric instabilities, some with distant magnetic-field-line reconnection, and some with the local feedback of ionosphere to magnetospheric energy input. All types of aurora involve an interplay of magnetosphere-ionosphere coupling.

Auroral forms include quiet and growth-phase arcs, high-latitude arcs, diffuse aurora, omega bands, streamers, giant undulations, pulsating patches, and poleward boundary intensifications.

Overview of Science Goals:

The goals of this FST are: to establish a definitive magnetic mapping between the aurora in the atmosphere and the source location in the magnetosphere; to determine a definitive answer as to what processes in the magnetosphere are producing the various types of aurora; to assess the energy conversion processes associated with auroral forms and to assess the impact that these auroral processes have on the magnetosphere and the ionosphere.

Applicability to NASA Heliophysics and LWS:

The first LWS-program objective concerns the response of the magnetosphere-ionosphere-thermosphere system to solar wind driving: this FST deals with the complex transformation of energy in the nightside magnetosphere that gives rise to visible manifestations in the atmosphere. This FST is applicable to three SSAs: SSA-1 (Geomagnetic Variability), SSA-5 (Ionospheric Scintillation), and SSA-6 (Radiation Environment) and it is also applicable to the space-weather problem of spacecraft charging.

Two key questions for future research in the NRC Decadal Survey are addressed by this FST. The first is “How Does Earth’s Magnetosphere Store and Release Solar Energy?”, with the subquestion “What are the interactions and feedbacks that connect the magnetosphere, solar wind, and ionosphere?” The second question is “How Does Earth’s Atmosphere Couple to Its Space Environment?”

Envisioned Focused Science Topic Implementation Strategy:

The implementation strategy envisioned for this FST involves: coordinated research efforts involving auroral observations, ionospheric diagnostics, and magnetospheric spacecraft measurements, aided by theory, plasma simulation, and global modeling;
the development of innovative methods to determine magnetosphere-ionosphere magnetic connections; the development of innovative quantitative methods to determine the spatial extent and temporal evolution of the transient aurora forms such as streamers and poleward boundary intensifications; research efforts studying the statistical connections between auroral occurrence and observed magnetospheric processes; research efforts studying the connections between low-altitude particle measurements and equatorial particle measurements.

Understanding Space Weather Effects and Developing Mitigation Strategies for Human Deep Space Flight

Introduction / Focused Science Topic Description:

With an increasing emphasis on deep space travel by NASA and other international agencies, hazardous space weather effects on human health and mission operations are of critical topical importance. Beyond the Earth's protective magnetosphere, humans are exposed to harmful solar radiation -- both continuously and via sporadic bursts of high radiation doses due to solar flares and bulk flows in the solar wind. Beyond in-transit exposure challenges, violent space weather and solar cyclical variability also result in hazardous conditions at lunar and planetary destinations.

Understanding the potential variability in the radiation environment with respect to solar conditions, knowing the biological risk level with respect to this time-varying environment, anticipating severe near real-time changes in that environment on an operationally useful timescale, and being able to rapidly respond to and mitigate hazardous conditions are of paramount importance to exploring within our solar system.

Overview of Science Goals:

The ultimate goal of this FST is to pull together the relevant information from other FSTs and science results from relevant research groups to provide the information needed to protect astronauts. Critical needs, applicable to both in transit and at the final destination, include solar radiation background level biological hazards that vary with the solar cycle and with dynamic space weather events; high energy particle exposure risks associated with solar eruptions; and mitigation strategies for predicting and protecting against harmful exposure.

Applicability to NASA Heliophysics and LWS:

The LWS program is founded on understanding the connection of the Sun to the heliosphere and geosphere. Fundamental to this effort is studying the Sun's effects on human society and humans directly, providing practical societal benefits. While NASA has been successfully pursuing Sun-Earth system studies for decades, the time has arrived to more earnestly pursue space weather effects on human space travel and mitigation strategies so as to precede upcoming missions. This topic has the added potential benefit of combining several interdisciplinary research groups from solar, heliophysics, engineering, and radiation biology backgrounds. This effort will build on space medicine efforts and foster collaboration between the space medicine and space weather research communities.

The knowledge gained from studying hazards to astronauts in deep space can also be applied to those in low earth orbit, space tourists, intercontinental airline travelers, and crews flying at high latitudes.

Envisioned Focused Science Topic Implementation Strategy:

To achieve the goals of the FST, exploration studies targeting the risks identified by the space-medicine community as influencing human spaceflight missions with regards to variable solar radiation exposure should be undertaken. These should include observational studies of the variability in the relevant radiation environment; studies aimed at predicting how this environment varies with solar conditions; studies focusing on the biological risk associated with these varying radiation levels; and studies which combine space medicine with space weather prediction physics.

Note:

In order for this FST to map back to LWS priorities, a new SSA (#7) should be added entitled "Space weather impact on human space travel". This addition is a natural progression of the priorities that the LWS program has undertaken since its inception, expanding from first principles to human application.

Solar Photospheric Magnetic Fields

Introduction / Focused Science Topic Description:

One of the primary goals of the LWS program is to achieve a quantitative understanding of how the Sun influences the Heliosphere and Earth's magnetic environment. A key aspect of understanding this interaction is the ability to quantitatively describe, and ultimately predict, both the local and the global solar corona and the inner heliosphere. A crucial input to models of the corona and solar wind, whether they be empirical or physics-based, is the magnetic field at the solar photosphere. Current global models of the solar corona and inner heliosphere frequently use global magnetic maps derived from photospheric magnetograms that are available from a number of ground- and space-based observatories, including, but not limited to: GONG, SOLIS, MDI, HMI, and soon PHI data from Solar Orbiter.

However, a number of issues make it difficult to use these various data to their fullest extent. For instance, difficult-to-correct zero-point offsets in magnetograms mean that measurements often differ substantially from one instrument to the next, making it difficult to generate global maps of the Sun needed to adequately model the coronal and solar wind, especially in a time-dependent manner. In addition, the fields in the polar regions are poorly observed, and line-of-sight (LOS) magnetograms (rather than the potentially available vector measurements) are often used to reconstruct the radial photospheric field. Ideally, time sequences of global maps that smoothly assimilate new data (including far-side measurements) would be made available to drive global models and provide a real-time forecast of the state of the heliosphere.

Overview of Science Goals:

The goals of this focused science topic (FST) will be to obtain a quantitative understanding of the sources of these calibration issues (e.g., zero-point offsets), to develop adequate methodologies to correct or mitigate them, to develop methods for correcting for poorly observed polar field contributions and far-side field contributions, and to develop techniques for incorporating vector magnetic fields, in addition to fields derived from LOS observations, into radial field maps. From these efforts, the goal is to produce the best quantitative maps of the radial magnetic field at the photosphere for the purposes of predicting coronal and solar wind parameters (e.g. solar wind speed, IMF polarity, coronal hole boundaries, open magnetic flux, plasma parameters, etc.).

Applicability to NASA Heliophysics and LWS:

This proposed topic is essential to nearly all of the Strategic Science Areas (SSAs), but is especially important for SSA-0 (Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and Inputs to Earth's Atmosphere), as it directly addresses the magnetic outputs from the sun. It also directly addresses, SSA-1 (Geomagnetic Variability), SSA-3 (Solar Energetic Particle), and SSA-6 (Radiation Environment) as it works to improve the inputs to the magnetic drivers of each of these effects.

This topic addressed Key Science Goal 1 of the Decadal Survey, namely to "Determine the origins of the Sun's activity and predict the variations in the space environment." Improving the fidelity and calibration of photospheric magnetic fields are critical for achieving many of the Solar and Space Physics Decadal Challenges. Namely, “SHP-1 Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere” requires an accurate measurement of the solar magnetic field as a function of time; “SHP-2 Determine how the Sun’s magnetism creates its hot, dynamic atmosphere” requires knowledge of the solar magnetic field, which currently is most accurately measured by these photospheric observations, and “SHP-3 Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere” again requires detailed and accurate knowledge of the photospheric magnetic field evolution.

Envisioned Focused Science Topic Implementation Strategy:

The following types of investigations would be most likely to achieve the goals of this Focused Science Topic: studies that intercalibrate data from different missions (e.g., SOHO/MDI and SDO/HMI), and ground based data (e.g. NSO/SOLIS and NSO/GONG), leading to the ability to routinely merge them and to form longer time series of data; studies that can provide an absolute calibration to these data providing a best estimate of the Sun’s magnetic field; studies that aim to resolve the issue as to why different magnetogram field values can differ from one another by more than a factor of two; studies that apply optimization strategies over large magnetogram data sets; studies which apply machine learning techniques to address magnetogram artefacts and intercalibration issues; quantitative characterization and assessment of the accuracy of different techniques used to estimate and incorporate the Sun’s polar magnetic field in maps; studies that combine vector magnetograph data (when available/feasible) with line-of- sight data to improve the estimate of the Sun’s global radial magnetic field; studies that incorporate estimates of the Sun’s field not visible from Earth, such as helioseismic far-side images.

Magnetospheric and Ionospheric Processes Responsible for Rapid Geomagnetic Changes

Introduction / Focused Science Topic Description:

Geomagnetically induced currents (GIC) are a hazardous space weather phenomenon, which can cause serious damage to critical infrastructures such as electric power transmission systems and pipeline networks. Although the observation of GICs is limited, they are closely correlated with geomagnetic disturbances, and qualified geomagnetic field data have been collected for several decades. Major GIC events take place during extremely intense storms, and it is generally known that the intensity of the GICs depends on the rate of the change of ground geomagnetic disturbances. It still remains to be understood under what conditions the rate of the change of geomagnetic disturbances becomes extraordinarily large, what magnetospheric and ionospheric processes are responsible, and if there are any preconditions for such processes to take place and grow to extreme levels. The answers are probably different at different latitudes, and they may also depend on solar wind drivers. For tackling these issues, systematic studies including both satellite and ground observations, with the aid of global modeling are highly required.

The Heliophysics community now has the unprecedented coverage of satellite data from the solar wind to the inner magnetosphere including data from missions like THEMIS, Van Allen Probes, and MMS. Considering that qualified ground data have been accumulated for several decades, we can also revisit historical data sets including global auroral images taken by satellites such as Polar and IMAGE. This topic can benefit from a wide range of current and past, and satellite and ground data sets.

Overview of Science Goals:

Determine the solar wind parameters, magnetospheric conditions, and ionospheric properties that affect the rate of the change of geomagnetic field in the coupled solar wind - magnetosphere – ionosphere system.

Applicability to NASA Heliophysics and LWS:

The suggested topic is the central issue of SSA-1 “Geomagnetic Variability” and is also related to SSA-0 “Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth’s atmosphere.” The first two objectives of the LWS program are: 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. 2. Obtain scientific knowledge relevant to mitigation or accommodation of undesirable effects of solar variability on humans and human technology on the ground and in space. GICs are one of the primary targets for the 2nd LWS objective quoted above. For the 1st LWS objective, it is critical to identify and understand magnetospheric and ionospheric processes that cause rapid geomagnetic changes potentially hazardous to ground infrastructures. Therefore, the suggested topic is very coherent with the overall goal of the LWS program.

This FST also addresses Decadal Survey Key Science Goal 2: “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs", and Decadal Science Challenge "Solar Wind-Magnetosphere Interactions (SWMI) - 3: Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind".

Envisioned Focused Science Topic Implementation Strategy:

This is an FST that will benefit from joint investigations of global modeling and data analysis techniques. Datasets to be included span from ground based (magnetometers, etc.) for identification of ionospheric conditions and geomagnetic field disturbances, to space-borne magnetospheric data (THEMIS, Van Allen Probes, MMS, Polar, IMAGE, etc.) for identification of the magnetospheric conditions, and solar-wind data: ACE, DSCOVR, OMNI.

Example studies could include: observational and numerical approaches for determining latitudinal variations of GIC sources and effects; numerical simulations using solar wind - magnetosphere - ionosphere coupled models with the goal of investigating the role of solar wind in driving GICs, and accompanying observational studies of correlations between GIC and various solar wind parameters; analysis of current and historic satellite and ground data sources during extreme GIC times with the goal of discovering any preconditions necessary for extreme GICs, and of any magnetosphere - ionosphere coupling processes involved; modeling of associated conditions related to extreme GICs.

Coupling of Solar Wind Plasma and Energy into the Geospace System

Introduction / Focused Science Topic Description:

The driving of the magnetosphere-ionosphere-thermosphere (MIT) system by the solar wind is fundamental to any understanding of magnetospheric physics and space weather. There are a number of outstanding gaps in the community's understanding of this coupling process which prohibits development of predictive abilities. It is known that the dayside reconnection rate largely controls the amount of coupling of the solar wind to the MIT system, but it is not known what parameters in the solar wind control the local and the total reconnection rates. It may be controlled by local plasma physics or by broader global parameters. In addition to this, there is a need to understanding what role (if any) plasma of magnetospheric and ionospheric origin may play in impacting dayside reconnection. The variability and turbulence within the solar wind and magnetosheath may also impact the efficiency of reconnection, however their relative roles have not been quantified. The types of solar wind variability that may lead to a higher levels of geoeffectiveness are important to understand. Additionally, the spatial extent of the reconnecting region at the dayside magnetopause greatly impacts the transfer of energy into the magnetosphere, yet it remains poorly known.

The coupling of energy and plasma into the magnetosphere may also take place through other physical processes outside of reconnection. These include viscous interactions or boundary waves such as Kelvin-Helmholtz. The parameters controlling these processes and the rate of plasma entry are not well defined.

There are also several outstanding issues associated with post-reconnection coupling. These include understanding how polar cap saturation may work and understanding how important solar wind coupling is to the polar cap ionosphere. Such coupling pathways may include large-scale reconfiguration of the magnetosphere's shape and dynamics.

Overview of Science Goals

The science goals of this FST are: To determine the parameters controlling the transfer of energy through dayside magnetopause reconnection; To establish the role of plasma from the ionosphere and magnetosphere in solar wind-magnetosphere coupling; To assess the parameters controlling non-reconnection coupling mechanisms; and To understand the post-reconnection reconfiguration of the magnetosphere and ionosphere system in response to extreme solar wind-magnetosphere coupling.

Applicability to NASA Heliophysics and LWS:

The FST outlines is a central pathway for the flow of energy from the sun to the geospace environment. It provides contributions to a broad span of SSA:

SSA-0: Physics Based Forecasting of Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth's atmosphere
SSA-1: Physics Based Geomagnetic Variability Forecasting Capability
SSA-2: Physics Based Satellite Drag Forecasting Capability
SSA-4: Physics Based Total Electron Content (TEC) Forecasting Capability
SSA-5: Physics Based Ionospheric Scintillation Forecasting Capability
SSA-6: Physics Based Radiation Environment Forecasting Capability

This focused science topic supports two of the four high level science goals 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;” and “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.”

Envisioned Focused Science Topic Implementation Strategy:

Successful implementation strategies may use coupled efforts of theory, numerical as well as other advanced modeling techniques, and data assimilation to understand global properties of magnetopause reconnection and energy transfer from the solar wind into the magnetosphere. These tools may also be appropriate for monitoring non-reconnection forms of coupling and global reconfiguration of the magnetosphere which are important to this focused science topic. The physics missing in some models such as MHD impose limitations on studying key effects in the coupling between the solar wind and the magnetosphere, therefore multifaceted efforts may be appropriate. Such multifaceted approaches may include constraining a model with observations or employing kinetic or hybrid models or components.

Diverse measurements of the solar wind, the magnetosheath, the magnetosphere, ionospheric convection, and geomagnetic activity may need to be combined to study the transfer of energy and plasma through the magnetopause. Appropriate datasets may include MMS, THEMIS, Cluster, ACE, WIND, Van Allen Probes, and GEOTAIL. Experimental datasets may also be combined to quantify the transport of plasma from the ionosphere to the magnetopause in response to solar wind driving.

Combining Models and Observations to Study CME Plasma Energetics in the Inner Corona

Introduction / Focused Science Topic Description:

Coronal mass ejections (CMEs) are one of the major manifestations of Space Weather, and constitute one of the major hazards posed by solar activity. One of the overarching goals of the Living With a Star program is to predict their occurrence and geo-effectiveness. The latter is critically influenced by the amount of energy released in the eruption process to heat and accelerate CME plasmas, by the conditions of the solar corona and interplanetary space that the CME faces once launched, and by the CME's own magnetic field orientation. Active regions are the launch site of the majority of CMEs; they consist of complex magnetic field configurations often hosting a filament, which can dwell in their midst for a long time before being destabilized; they are intertwined with large scale structures and often are close to open field line regions. All this complexity contributes to guiding the CME trajectory in the initial part of the eruption, to determining the amount of energy released in the eruption as well as its distribution among the front, cavity and core components of CMEs, and to the eventual CME geo-effectiveness.

Once the eruption is started, the partition of the released energy between heating, acceleration, and the other terms, and their distribution within the plasma of the main CME components (front, cavity, and core) plays a critical role in the CME evolution. Several mechanisms that heat and accelerate CME plasmas have been debated , but no consensus has been found. A few studies have attempted to quantify the various energy terms using observations, but limitations in the cadence, field of view, timing and diagnostic capabilities of the available instruments have hampered a thorough evaluation of CME energetics. Theoretical model complexity and sophistication have greatly increased, but comprehensive predictions of CME energetics are largely unavailable, and have not been adequately tested against observations.

Increasingly more sophisticated interior-to-coronal models of solar flux emergence have provided new insights into the formation of complex, flare/CME productive active regions. Advanced data analysis techniques for observational inferences and data driven models are being developed to study realistic eruptive events. These techniques and models can also determine the evolution and relative importance of all terms of the energy equation for the plasma in each of the CME components. These models allow more direct comparisons with multi-wavelength observations of the solar atmosphere. In turn, available narrow-band and spectrally resolved observations of both CME eruption and host active regions provide strict benchmarks to model performance. Of particular importance are models' ability to predict spectral line emission, because such emission allows one to monitor the evolution of the plasma in all CME components regardless of their temperature.

Overview of Science Goals:

The goal of this focused science topic is to combine observations and modeling in order to 1) monitor the energetics of the plasma in all CME components during the early evolution of the CME; 2) determine how the energy released by the CME process is partitioned among the various energy terms; and 3) understand if and how such partition changes in different CME events. Specifically, this FST encourages, when available, the use of spectrally resolved observations, and the prediction of spectroscopic observables, for model validation. A few suitable topics for this FST are: modeling of CME eruptions and predictions of the energetics of the plasma in all CME components; statistical studies of the CME energetics; assessing model performance through detailed comparison between predicted and observed narrow band and spectrally resolved emission from the fleet of NASA space observatories.

This investigation will be of particular interest to, and serve as a bridge between, the CME and the active region modeling community on one side, and the observational community on the other. The desired final outcome will be CME eruption models that are able to successfully reproduce the array of different observables produced by the fleet of NASA space missions, evaluate the energetics of all CME components, and determine its variability in different CMEs. The products of this FST will be of maximum relevance to the Space Weather forecast community.

Measures of success will be: the ability to predict CME energetics from an active region eruption as a natural final outcome of the modeled active region evolution; successful integration of data (narrow band, high spectral resolution) into the model; successful prediction and forward modeling of spectral line intensities, widths and centroids of multiple species at different temperatures before and during the eruption; statistical studies of quantitative CME energetics.

Applicability to NASA Heliophysics and LWS:

The successful proposal will be directly relevant to two scientific goals of the Heliophysics Decadal Survey, specifically the first (*"Determine the origins of the Sun's activity and predict the variations of the space environment"*) and the fourth (*" Discover and characterize fundamental processes that occur both within the Heliosphere and throughout the Universe"*). Furthermore, the successful proposal will need to be specifically designed to address the Strategic Science Area SSA0 — *Physics Based Forecasting of Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth's atmosphere*.

Envisioned Focused Science Topic Implementation Strategy:

The success of this is FST depends on the close synergy of theory and observations, and thus it requires the work of teams composed by both theorists and observers. Investigations may include, but are not limited to: modeling flux ropes nested into active regions from their formation, evolution and eruption; systematic investigation of high resolution and/or narrow-band signatures of energy release in an active region and in a CME during the eruption; modeling of the energetics of all CME components during the early phases of CME eruption; determining CME energetics variability.

Atmospheric Evolution and Loss to Space in the Presence of a Star

Introduction / Focused Science Topic Description:

The presence of an atmosphere is thought to be one of the fundamental criteria for sustaining a habitable environment. Despite the wealth of measurements from Earth, Mars and Venus, we still do not understand the critical factors that determine the ultimate loss of an atmosphere to space. For example, does a magnetic field inhibit or amplify the atmospheric loss? While estimates of the total escape rates for Mars and Venus are in the order of 10^25 particles per second, estimates for Earth are spread in a wider range from 10^24 to 10^26 particles per second mainly due to the complicated ionospheric and magnetospheric processes and pathways for ultimate escape.

Given the wealth of data from Earth (Cluster, MMS, and many more), Mars (Mars Express, MAVEN), Venus (Venus Express), Titan (Cassini), Mercury (MESSENGER), and Pluto (New Horizons), it is timely to make a quantitative assessment of our current understanding of atmospheric loss and the factors that control it, both from an experimental view point, but also from a theoretical one.

In addition, given the increasing number of exoplanets discovered in the habitable zone and ongoing efforts to constrain the intrinsic magnetic fields of exoplanets through radio observations, there is a growing need for quantitative data and assessment from our own solar system. This research topic presents a great opportunity for the heliophysics community as a whole to strategically position itself in the new era of increasing interest for studies concerning the habitability of other worlds.

Overview of Science Goals:

The overarching goal of this FST is to explore the role that an intrinsic magnetic field plays in atmospheric loss to space. In order to achieve that goal, investigation of magnetosphere - ionosphere coupled processes that lead to atmospheric loss in a magnetized planet is necessary. Comparing and contrasting the processes that lead to atmospheric loss from planets with strong, weak, or no magnetic fields could potentially reveal the planetary conditions under which, magnetospheric and ionopheric processes dominate over other processes that can lead to the loss of a planetary atmosphere.

Applicability to NASA Heliophysics and LWS:

The FST addresses SSA-0 “Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth’s atmosphere”, and goals 2 “Develop a fuller understanding of how and to what degree variations in the Sun’s radiative and particulate outputs will in conjunction with other forcing factors affect regional and global climate in the present century”, and 4 “Deliver understanding and predictive models of upper atmospheric and ionospheric re-sponses to changes in solar electromagnetic radiation, and to coupling above and below” as those are stated in the executive summary of the 10 yr vision of the LWS program. The topic also addresses the “Sun-Planet and Star-Exoplanet Connections” thrust of “Future Opportunities and Challenges” of the LWS 10 yr vision.

Finally, this FST addresses Decadal Survey Key Science Goal 2: “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs”, and Decadal Science Challenges “Solar Wind-Magnetosphere Interactions (SWMI) - 3: Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind” and “Solar Wind-Magnetosphere Interactions (SWMI) - 4: Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems”.

Envisioned Focused Science Topic Implementation Strategy:

Potential studies to address this FST include: Investigations of atmospheric loss processes based on analysis of observational datasets from multiple missions that have visited different planets with different levels of intrinsic magnetic field strength (a few examples of such missions are mentioned in the introduction above); Numerical investigations of atmospheric loss processes, including, among others, interactions of the planet with the solar wind, based on different planetary magnetosphere - ionosphere - atmosphere coupled models.

Hemispherical Asymmetries in Magnetosphere-Ionosphere-Thermosphere Coupling Processes: Fundamental Causes and Myriad Manifestations

Introduction / Focused Science Topic Description:

While both northern and southern polar upper atmospheric regions are closely linked through the magnetosphere, the coupling is often not symmetrical. The reasons for this are not fully understood, and certainly can not yet be predicted. Fundamentally, these asymmetries evolve from geographic and/or geomagnetic aspects of Earth, as well as possible effects that arise directly from the solar wind. Examples of this asymmetrical coupling include magnetic pulsations, ion outflows, field-aligned currents, electromagnetic energy (Poynting) flux, auroral particle precipitation, high-latitude ionospheric convection, currents and conductance, ionospheric electron densities and thermospheric winds and mass densities. Many of these hemispheric asymmetries can be traced back to a handful of fundamental causes including interplanetary magnetic fields, solar illumination, Earth's magnetic field (e.g., different offsets between magnetic and geographical poles, differences in field strength at conjugate regions, displacement of the magnetic equator from the geographic equator) as well as land-sea distribution. There are also hemispherical differences at the mid and low latitudes, and associated coupling processes between the hemispheres (e.g. magnetic lines of force, winds, and electrodynamics), that lead to differences in the neutral atmosphere and plasma. This focused science topic calls for observational and modeling studies that will establish relationships between the many types of hemispheric asymmetries and their fundamental causes.

Hemispheric asymmetries are often investigated through statistical averaging of individual variables and/or idealized simulations focused on one causal effect. Even though such investigations are valuable, the underlying physical processes are dynamic and complex, resulting from multiple asymmetric coupling mechanisms that are operating simultaneously. It is important to move away from a dichotomous paradigm of treating each type of hemispheric asymmetry in isolation.

Overview of Science Goals:

The efforts described above show that interhemispheric differences in coupling are ubiquitous. The topics addressed, while not coordinated, span a wide range and include a number of fundamentally important concepts, ideas that are essential for the development of successful modeling efforts. These ideas also feed directly into LWS goals, including understanding thermospheric effects and better modeling of total electron content and neutral atmospheric densities.

The main goal of this FST is to unveil the fundamental causes of hemispheric asymmetries in the magnetosphere-ionosphere-thermosphere coupling processes. This will lead to an improved physics-based understanding of time-evolving structural changes in thermospheric mass density and ionospheric electron density (TEC) between the hemispheres. A subgoal is to determine which drivers, e.g. the solar wind, the offset between the geographic and geomagnetic sources, generate the observed asymmetries and how these drivers interact with each other. Of particular importance is to determine how these asymmetries affect TEC and neutral density.

Applicability to NASA Heliophysics and LWS

This FST addresses SSA- 2: Physics Based Satellite Drag Forecasting Capability and SSA-4 (Total Electron Content). It also addresses the Decadal Survey's Atmosphere Ionosphere Magnetosphere Interactions Science Goal 4: Plasma-Neutral Coupling in a Magnetic Field – How do neutrals and plasma interact to produce multiscale structures in the AIM system?

Envisioned Focus Science Topic Implementation Strategy:

Potential approaches to conjugate asymmetry studies might depend on the region being addressed. For example, hemispherical asymmetries in the ***polar regions*** could be quantified and modeled by: measuring the differences between the Arctic and Antarctic polar vortices; observing the differences in the magnetic local time (MLT) location of aurora and its relationship to IMF By and Bz; and comparing the differences in high latitude convection, cross polar cap potentials, and Joule heating. Other polar-focused studies could concentrate on identifying various processes (drivers) that cause hemispheric asymmetries. For example, coupled numerical models could incorporate data utilizing a number of recent ground-based and space-based conjugate observations (e.g., ground-based: magnetometer chains, GPS TEC, SuperDARN, and all-sky imagers; and satellite-based, Iridium/AMPERE, DMSP, TIMED/SABER, TIMED/GUVI, GOLD). This same data could also be used to validate the models.

Studies observing ***low and mid-latitude*** hemispherical differences might employ numerical modeling and observational analysis of ionospheric plasma and neutral densities. An example approach might use both observational and modeling techniques to study general thermospheric circulation features driving hemispheric differences in winds and composition.

Sun-Climate Theme:

Variability and Predictability of the Solar-Driven Earth System

Introduction / Sun-Climate Theme Description:

This theme will encourage a variety of studies of long-term variations of the solar input that are important for geospace, the terrestrial response to this time-varying input, as well as solar mediation of terrestrial processes on long timescales. Variations in solar electromagnetic and particle input to geospace, as well as solar modulation of extra-solar input, consist of violent, short-term events such as solar eruptions (space weather) as well as longer-term, quasi-periodic phenomena such as daily-to-decadal variations in irradiance and high-speed solar-wind streams. The accumulated effect of these variations directly influences the geospace climate. In addition, solar-induced variations in the coupling of various process throughout geospace give rise to important, second-order effects. Of primary interest are solar-driven impacts on regional and global weather and climate from the surface throughout geospace, on time scales ranging from months to centuries.

A predictive capability requires detailed knowledge of the physical processes by which solar forcing impacts the Earth's climate. Therefore, proposed studies should emphasize acquiring or refining a mechanistic understanding of how solar variability and solar-driven geomagnetic variability lead to or alter atmospheric structure and coupling, with the intent of including these processes in global climate models. The overarching goal of this focused science topic is to acquire the capability to reliably predict the long-term effects of solar and geomagnetic variability on society. It is expected that proposals submitted in response to this solicitation would focus on specific aspects of this goal.

Overview of Science Goals:

On the solar side, the primary gaps to be filled are a better understanding of historical proxies for variations in solar irradiance, particle, and magnetic inputs.

On the terrestrial side, the primary gap to be filled is knowledge of the processes that indirectly amplify the effects on the Earth of solar variability and solar-driven geomagnetic variability. These poorly understood processes are assumed to involve wave-induced coupling of different atmospheric regions. Work conducted as part of this topic will elucidate how and the extent to which coupling mechanisms redistribute solar and magnetospheric energy at Earth. It will describe the radiative, magnetic, dynamical, and chemical feedbacks that control weather and climate throughout the atmosphere, and that link the regions driven directly by solar influences to the troposphere where human activities are concentrated. To name just a few examples, work conducted as part of this theme will enable better predictions of such things as the earth system response to solar and geomagnetic forcing under future climate scenarios; the impact on weather and climate of a Maunder-like minimum; long-term solar-driven impacts on large-scale atmospheric and ocean circulations; and the effects of atmospheric dynamical perturbations such as sudden stratospheric warmings on how the atmosphere responds to solar forcing.

Applicability to NASA Heliophysics and LWS:

The sun–climate theme within LWS TR&T has unique societal relevance. It also is a uniquely challenging interdisciplinary theme that extends well beyond the traditional heliophysics domain by involving many aspects of the geosciences. Despite the complex web of physical processes to be studied, LWS TR&T has proven to play an important role in the overall study of climate and climate change in particular because it stimulates the expertise close to the core of the LWS goals: understanding of solar and heliospheric activity, and the physical processes that couple that activity to the uppermost layers of the Earth's climate system.

This addresses Decadal Survey Key Science Goal 2: "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere,and atmosphere and their response to solar and terrestrial inputs." The topic is relevant to SSA-0. In particular, it addresses "the responses of Earth's atmosphere" to "solar electromagnetic, energetic particle and plasma outputs driving the solar system environment and inputs to Earth's Atmosphere." Work accomplished as part of this topic will enable the science community to move beyond simple correlations between solar variability and climate parameters, and instead to define the relevant mechanistic connections. This topic encompasses the aspect of SSA-0 that seeks to gain "a physics-based understanding that will enable forecast capabilities...with a particular focus on a better understanding of the .... implications for the space environment and responses of Earth's atmosphere."

Envisioned Sun-Climate Theme Implementation Strategy:

The strategies envisioned to be required for successful achievement of this Sun-Climate theme are: measurement, modeling, and prediction of solar inputs such as: modulation of irradiance, energetic-particle flux, and solar magnetic field modulation of galactic cosmic rays on short time-scales (accumulation of events) and long time scales (historical records); and measurement, modeling, and prediction of terrestrial responses, such as: response to variations in the input, coupling, and transport within geospace. Relevant observational sources for these studies include: DMSP, GOLD, ICON, GRACE, SWARM, TIMED-GUVI, TIMED-SABER, ISRs, FPI, as well as observations of the varying solar irradiance, particle, and magnetic inputs.

This effort would require coordinated modelling and observational effort. Collaborative research, i.e. between the atmospheric and geospace science communities, is encouraged, as well as collaborative efforts between these research communities and the operational (orbit determination and satellite tracking) space weather communities.

Tools and Methods:

Data Science and Analytics

Introduction / Tools and Methods Topic Description:

A main objective of the LWS program is to develop the physics-based understanding and forecasting capability stated in the SSAs as most critical to predicting the near Earth space environment. Historically, first-principles physics modeling has been a major established framework for producing models needed for such understanding and forecasting. However, in the past, heliophysics data enabled the development of models using statistical frameworks. Empirical approaches had the advantage of being fast and simple, and have delivered a measure of dependencies between a set of input parameters and a set of output parameters.

Statistical methods at least partly decouple the ability to forecast from a first-principles understanding, which can be powerful in complex multi-coupled systems. Even for a system in which the first principles are known, without perfect knowledge of the initial or forcing conditions, there may be so many factors at play that a probabilistic approach still has an important role to play.

The ever-increasing availability of heliophysics data is permitting newer data science and analytics techniques that go beyond the traditional methods. Tools that can obtain nonlinear relationships and can untangle the drivers behind various behaviors can complement deterministic and even empirical analyses. Such approaches rely heavily on data, with or without a priori knowledge (e.g., deterministic models, prior probabilities) [McGranaghan et al., 2017].

Over the last several decades, researchers in the fields of mathematics, information science, computer science, machine learning, data mining, etc., have developed tools that can handle complex nonlinear relationships. In the case in which some a priori knowledge is used, the assimilation of large amounts of data can move the state of a model in the direction of representing the actual conditions, much as modern weather forecasts do. Advances in data assimilation techniques and development of new ground-based and satellite-based observation systems now make it possible to build the global data sets needed to initialize and validate whole atmosphere forecasts.

Absent a priori knowledge, or even independently of it, machine learning techniques are also emerging as ways of elucidating hidden relationships. Models based on these methods may to a certain extent operate as a "black box" for which the data are input and a functional forecast output without insight into why the box, i.e., model, works the way it does; in this sense they are akin to empirical modeling. Reinforcement learning, support vector machines, and various types of neural networks provide a basis for statistical inference. They also have the potential to enable discovery science [Pankratius et al., 2016]. These are possibly also a way of leveraging the highly diverse types of measurements inherent to heliophysics science.

This Tools and Methods topic recognizes that many knowledge gaps in the Strategic Science Areas can be successfully attacked through data science approaches, which here include data assimilation, data mining, machine learning, statistical and informational methods, and/or artificial intelligence methods. This program calls on the community to develop innovative uses or applications of data science and analytics methods to address SSA-0 through SSA-6 going explicitly beyond traditional empirical regression analyses. This program encourages cross-disciplinary methods from the field of data science and their application to the Living With a Star domain. The program encourages interdisciplinary collaboration, research at the intersection of traditional and new data science and analytics approaches, and development of tools to analyze the full data life-cycle. With past, recent, and upcoming satellite missions such as SDO, MMS, PSP, GOLD, ICON, a GRACE follow-on, and COSMIC-2, combined with the ground-based instrumentation available from single source or distributed arrays, the Heliospheric community has at its disposal an unprecedented breadth and depth of data.

Overview of Science Goals:

Projects awarded under this program have the option of applying as a stand-alone Tools and Methods project (Option 1 below), or to apply as a Tools and Methods focused contribution to one of the other FST areas in this NRA (Option 2 below). In either case, the proposed solution to addressing the chosen science problem should specifically rely on a data assimilative, and/or machine-learning algorithm. Efforts are encouraged that enable discovery science, provide forecasting capability or some combination of the two.

Proposers should address the several challenges that exist in using data science approaches with respect to volume, speed at which they can be analyzed, and, particularly in heliophysics, diversity of the data, and uncertainties associated with both the measurement inputs and thus the outputs. Goals of projects awarded in this program should be able to quantify performance along measures including but not limited to accuracy, veracity, and robustness. While the individual targets and benchmarks for the performance measures will depend on the science goal being addressed and the nature of the methods being proposed, since they all rely on the use of data, proposers should offer a quantitative analysis of, or identify an approach for how, measurement uncertainties figure in and propagate through their data science and analytics techniques.

Applicability to NASA Heliophysics and LWS:

Option 1) This Tools and Methods program is potentially applicable to any of the SSAs. Proposers should identify and call out specifically which SSA applies for their chosen data science and analytics approach, who the users would be, and how the chosen science area benefits from this approach.

Option 2) To apply jointly to an FST, proposers should identify which FST in the NRA is, and clearly show how their methods will contribute to the solutions for and provide insight into the science goals of that FST.

With either option, the goal of this program would support the other SSAs/FSTs. In doing so, it would be responsive to the NASA Heliophysics Decadal Survey and Living With a Star program. This topic ties in with ongoing and emerging interdisciplinary work applying data-assimilative algorithms and machine learning techniques with domain-specific expertise. It is identified in the LWS Science Definition document that "theory, modeling, and data" in service of "coupling in the Sun-Earth system" are within scope. This Tools and Methods program falls within that but explicitly broadens the interpretation to include emerging areas of data analytics. This has been identified in other agencies, e.g., the NSF Ten Big Ideas (e.g., Convergent Research, Data Revolution), as well as the multi-agency Space Weather Action Plan.

Envisioned Tools and Methods Implementation Strategy:

Examples of responses to this FST might include, but are not limited to, data-driven approaches to ionospheric prediction; the use of ensemble Kalman filtering for ionosphere-thermosphere coupling investigations; data assimilation using Van Allen Probes for radiation belts and radiation belt-ionosphere/atmosphere coupling; "facial recognition" for the sun or corona; finding connections in a complex driver/response system or multi-dimensional systems with (too) many degrees of freedom (e.g., solar wind driving vs magnetospheric state; magnetotail dynamics and auroral displays; auroral energy input and thermospheric wave activity); whole atmosphere data assimilation for improved prediction of solar-terrestrial coupling; pattern recognition using multiple overlapping images of the aurorae for geospace science.