

# **Living with a Star Targeted Research and Technology Report**

**October 14, 2016**

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## 1. Introduction

This is the 2016 report of the deliberations of the NASA Living with a Star (LWS) Targeted Research and Technology steering committee (TSC). To quote from the 2003 LWS TR&T Science Definition Team report, which set the foundation for both this program and its steering committee, “the Targeted Research and Technology (TR&T) component of LWS provides the theory, modeling, and data analysis necessary to enable an integrated, system-wide picture of Sun-Earth connection science with societal relevance.” The TSC was to be “formed to design and coordinate a TR&T program having prioritized goals and objectives that focused on practical societal benefits.” The committee is formed each year to deliberate topics proposed by NASA Headquarters (HQ) and by the committee itself, and to develop science goals and objectives for the program, in the form of Focused Science Topics and Strategic Capabilities.

Our charge from NASA HQ for 2016 was to:

- Develop an assessment on a new procedure for developing annual science topics, focusing on community involvement.
- Develop an assessment on how potential Space Weather Action Plan (SWAP) mandatory spending for LWS could be effectively applied to SWAP research actions on a short timescale.
- Develop an assessment on connections between SWAP goals and LWS TR&T goals.
- Develop an assessment on how to develop and measure metrics tracking how well products resulting from the TR&T program are transferred to societal benefits.
- Develop ~15 new Focused Science Topics for consideration by NASA for ROSES 2017.

We met as a committee for three meetings, on:

- February 8-9, 2016: We discussed the procedure for selecting new FSTs and mechanisms by which the LWS program could utilize SWAP mandatory spending for targeted for LWS. Our two assessments were presented to the NASA Heliophysics Subcommittee (HPS) on March 1-2, and are included below.
- May 16-19, 2016: We developed 15 draft FSTs from 57 community contributed topics. The 15 draft topics were published on the TR&T website for a period of approximately 2 months for comment by the community.
- September 17-19, 2016: We finalized the 15 FSTs using the community input for each topic. We discussed how the SWAP actions connect to the SSA’s of the LWS TR&T program, and developed an assessment and a connectivity matrix based on this discussion. We also began the discussion on defining metrics by which the progress of the LWS TR&T program can be measured. The 15 FSTs and the assessments and plans which resulted from these discussions were presented to the NASA Heliophysics Subcommittee on October 25, and are included below. The SWAP-TR&T connections matrix we developed is attached as a spreadsheet.

### Other key dates and activities:

- A public input period for suggested science topics was held for a 6 week period starting March 13.
- An online town hall was held April 8, introducing the new topic development process, and soliciting community input for these science topics.
- 13 draft science topics were released online for comment May 30, and two additional topics were released June 21. The public comment period for these draft topics was June 1 - July 21. Town halls at the AAS-SPD, CEDAR-GEM, and SHINE meetings were held during this comment period to introduce and discuss these draft topics.

### Strategic Science Areas (SSA's):

For reference in the discussions below, the Strategic Science Areas, as developed in the 2013 and 2015 LWS TR&T Steering Committee reports, and which serve to guide long term areas of targeted systems science in the TR&T program, are:

- 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-3: Physics Based Solar Energetic Particles 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

## **2. Assessments:**

The following four assessments are recorded below as presented to the HPS

- Assessment on Procedure for Development of Annual TR&T Science Topics
- Assessments on the Space Weather Operations, Research and Mitigation (SWORM) Task Force Report
- Assessments on the Connections Between the LWS TR&T Goals and the SWAP Goals
- Plans for future assessment on “Metrics for Evaluating Progress Towards Achieving LWS-TR&T Goals”

## **Assessment on Procedure for Development of Annual TR&T Science Topics**

It is vital for the success of the Living with a Star Targeted Research and Technology (LWS TR&T) program that there be active community engagement in the development of annual TR&T science topics. The LWS TR&T Steering Committee (TSC) assesses that the following procedure should be followed to solicit and obtain community input for and to then develop these science topics:

### Encourage active community input to TR&T science topics:

- Announce call for community input to science topics through SPA news, Solar News, and other newsletters and e-mail lists every 2 weeks for a 6 week input period.
- Produce a short summary and explanation of this call for presentation at conferences, in newsletters, and at individual institutions.
- Hold an Online town hall where the call for topics is explained and community questions and input are solicited.
- Release the suggested science topics online as they are submitted, without submitter identifying information. Include a comment box for each topic to provide a place for comments and discussion. This page should be archived.

### Draft science topics at second TSC meeting:

- At its second meeting, following the 6 week input period, the TSC develops draft science topics based on the community input received and based on the established LWS TR&T goals.

### Solicit community comment on draft TR&T science topics:

- Release (online) these draft science topics to the community for a comment period of at least 6 weeks.
- During this comment period, present these draft science topics at / via:
  - Conferences
  - Online town halls
  - Newsletters and e-mail lists

### Finalize science topics at third TSC meeting:

- At its third meeting, following this comment period, the TSC finalizes the TR&T science topics and compiles the TSC annual report, incorporating community feedback on the previously released draft science topics.

### Assessments for Future year TSCs

- Seek science topic input via:
  - Final write-up of LWS institutes.
  - Town hall and science discussion sessions at conferences.
  - Final write-up of LWS science teams.

## **Assessments on the Space Weather Operations, Research and Mitigation (SWORM) Task Force Report**

The LWS TR&T Steering Committee (TSC) recognizes that NASA's responses to the National Space Weather Action Plan (SWAP) tasks will require immediate and dedicated actions by the LWS program in addition to activities already underway. The following represent the TSC assessments on a process by which the LWS TRT Program Office can respond to and carry out LWS-related SWAP activities.

**Assessment 1:** The TSC suggests the following short-term task to assist NASA in carrying out its SWORM benchmarking activities:

- NASA should establish LWS SWORM Tiger Teams to support the five SWORM benchmarking activities. These teams would be distinct from, but complementary to current LWS teams, such as the Focused Science Topic teams and the Strategic Capability teams.
- The charter of each Tiger Team would be to
  - Assist and support the government study board by providing assessments as directed and by reviewing the gap assessment performed by the governmental study board. Specifically, the teams would identify gaps in science, perform evaluation of uncertainties, and identify collections of available data, as well as critical missing data.
  - Identify and implement any short-term science actions that need to be taken to feed into the Phase-2 improved benchmarking process. Science actions could include synthesizing models and data, and providing tools relevant to benchmarking.
- A fast-track selection process should be implemented so that the Tiger Teams have sufficient time to complete their tasks within the deadlines identified in the SWAP. Based on these deadlines, the announcement-to-selection process should be no more than a few months.
- For this fast-track process, no restrictions should be put on proposal teaming structures in order to maintain flexibility to best serve the SWORM activities. For example, both team proposals and individual proposals should be allowed for each benchmarking topic, thus allowing the LWS Program Office the flexibility to form the tiger teams from these proposals and/or to select individual investigations.

### **Assessment 2:**

With regards to the longer-term activities identified in the SWAP report, the TSC assesses that it should trace out the correspondence between all the SWORM actions to which NASA is contributing and the LWS TR&T Strategic Science Areas (SSA's). Based on this correspondence, the TSC should develop assessments at its next meeting detailing how the TR&T's SSA-targeted activities can feed into and/or address NASA SWORM actions. In future years, the TSC should include Tiger Team feedback to the program in order to more closely align TR&T activities to the SWORM goals.

## **Assessments on the Connections between the LWS TR&T Goals and the SWAP Goals**

### **Assessment:**

The Living with a Star Targeted Research and Technology (LWS TR&T) program provides leverage for making scientific advancements and developing predictive capabilities in the research arenas that are critical for achieving many of the actions laid out in the Space Weather Action Plan (SWAP).

Numerous SWAP actions organically map to LWS TR&T Strategic Science Areas (SSAs, *The LWS 10-Year Vision beyond 2015*) that provide long-term objectives for advancing LWS science in the development of space weather forecasting capabilities. These connectivities are laid out in the spreadsheet: “TR&T-SWAP Matrix” in the Appendix.

The LWS TR&T Steering Committee (TSC) should establish LWS SWORM Targeted Topics to support the SWAP goals, particularly Goal 1 (Establish Benchmarks for Space-Weather Events), Goal 4 (Improve Assessment, Modeling, and Prediction of Impacts on Critical Infrastructure) and Goal 5 (Improve Space-Weather Services through Advancing Understanding and Forecasting).

These LWS SWORM Targeted Topics would be distinct from, but complementary to, current LWS research topics such as the Focused Science and the Strategic Capability topics, and implemented with the additional resources provided by SWORM related budget increases.

### **Assessment:**

Major advances in predictive capabilities for space weather, as identified by the SWAP, will require new and diverse sources of data. Given additional funding, LWS TR&T should incorporate a larger technology development program to support sensor and software advances necessary in accurate space weather specification and forecasting.

## **Plans for future assessment on “Metrics for Evaluating Progress Towards Achieving LWS-TR&T Goals”**

**Plan for a future assessment:** The LWS TR&T steering committee (TSC) plans to develop and track metrics for evaluating progress in TR&T programs. The goal of this effort will be to track the progress of SSA-oriented research in producing products which can be implemented into space weather forecasts. The TSC engaged in a lively discussion of this assessment during the 2016 session, and will continue the discussion in its next year of deliberations, with the goal of completing this assessment in 2017.



### **3. Focused Science Topics:**

- Mid-latitude and Equatorial Dynamics of the Ionosphere-Thermosphere System
- Origins, Acceleration and Evolution of the Solar Wind
- Ion Circulation and Effects on the Magnetosphere and Magnetosphere - Ionosphere Coupling
- Toward a Systems Approach to Energetic Particle Acceleration and Transport on the Sun and in the Heliosphere
- Coupling Between Different Plasma Populations by Means of Waves
- Probabilistic Forecasting and Physical Understanding of Extreme Events
- Understanding Physical Processes in the Magnetosphere--Ionosphere / Thermosphere / Mesosphere System During Extreme Events
- Understanding the Impact of Thermospheric Structure and Dynamics on Orbital Drag
- Solar Magnetic Inputs to Coronal and Heliospheric Models
- Understanding the Response of Magnetospheric Plasma Populations to Solar Wind Structures
- Heliospheric and Magnetospheric Energetic Precipitation to the Atmosphere and Its Consequences
- Understanding The Onset of Major Solar Eruptions
- Understanding Ionosphere-Thermosphere (IT) responses to high-latitude processes and Magnetospheric energy input
- Enabling Geospace System Science Through Imaging and Distributed Arrays
- Understanding Global-scale Solar Processes and their Implications for the Solar Interior

## **Mid-latitude and Equatorial Dynamics of the Ionosphere-Thermosphere System**

### **Target Description:**

It is well known that during magnetic storms heating occurs first at high latitudes . Energy is transferred from the magnetosphere to the ionosphere-thermosphere (IT) through Joule heating and particle precipitation. Equally well known are the dramatic positive and negative ionospheric storm effects that undoubtedly result from this input and the complex IT interactions. However, we do not understand how this energy and dynamics are transferred to mid- and equatorial latitudes to form the plasma density and total electron content (TEC) distribution observed there as well as irregularities/scintillation. To date much of what is known about the dynamics of mid-, low- and equatorial latitude electrodynamics is largely based on observations from a few incoherent scatter radars and individual single ground observatories. In very recent years extended ground GPS arrays have offered global scale dynamics from TEC observations and can potentially track the propagation of TIDs. Although much phenomenological insight has been gained into the complex dynamics at those latitudes, the link to physical processes that result in scintillation and TEC dynamics is not understood. It is not surprising that IT responses observed recently by satellites such as C/NOFS and recent ground instrumentation have been unpredictable and unexpected. Specifically, the significant longitudinal variability now seen in multiple IT properties is not at all understood and has become a barrier for the ongoing global density modeling effort that is necessary to improve TEC and scintillation forecasting capabilities.

There has been a lot of speculation on the possible causes of longitudinal electrodynamics variability, which includes: (a) the disturbance dynamo, which is the large-scale neutral wind system responsible for transferring energy from high to low latitudes and across the equator, and/or large scale atmospheric and ionospheric waves (TADs and TIDs) (b) the longitudinal difference in the neutral wind magnitude and direction, (c) the coupling between lower atmosphere and ionosphere (possibly source for non-migrating tides and localized gravity wave activity), (d) the longitudinal difference in the magnetic field orientation and magnitude at low latitudes. However, due to the uneven distribution of suitable ground-based instrumentation, and lack of consistent low-inclination missions, these speculations have not been validated or confirmed. The longitudinal distributions of ground-based instruments (GPS, ground magnetometers, imagers, radars, ionosondes, lidars, etc) are now getting better and can be utilized both for the low latitude longitudinal electrodynamics observations as well as for latitudinal transport of waves and energy from high latitudes to equatorial latitudes.

Understanding the latitudinal energy transport to from high to lower latitudes and the longitudinal variability of mid-, low-, and equatorial latitude electrodynamics is essential to the following LWS strategic science areas (SSA): SSA-4 Physics-based TEC Forecasting Capability, and SSA-5 Physics-based Scintillation Forecasting Capability

This topic is timely as it will advance our current state of understanding and capability to forecast scintillation and TEC structure at low latitudes and prepare the research path for multiple upcoming missions (ICON, GOLD, COSMIC-2)

### **Goals and Measures of Success:**

**The goal of this FST is to understand mid and low latitude plasma density structure that affects scintillation as well as TEC variability and to accurately model the physical sources that drive it.** Up-to-date simulation results should be compared with pertinent observations to quantify both our success level and the gaps in our understanding.

Measures of success will be:

- Specification of the longitudinal structure of low and equatorial latitudes of plasma density and plasma drifts
- Specification of vertical plasma motions
- Specification and quantification of the effect of energy transport (TIDs/TADs) to this longitudinal structure
- Quantification of a relationship between the longitudinal structure and scintillation effects. Is seeding required for the instability to grow? What is the dynamics or persistence time and spatial scales of the instability after it grows.

### **Types of Investigations:**

We seek investigations that will take advantage of historical, ongoing and future observations from space (e.g., C/NOFS, GRACE, TIMED, etc) and supporting observations from the growing deployment of mid-, low-, and equatorial latitude ground instrumentation of all kinds, and in combination with empirical and physics based models. Data assimilation techniques are also encouraged. Selected investigations should address any or all of the following scientific questions:

1. What is the mid-, low-, and equatorial latitude structure of plasma density, particularly during geomagnetically active periods, and how does the magnetic field longitudinal orientation and magnitude affect it.
2. How does the disturbance dynamo contribute to transferring energy from high to low latitudes and across the equator
3. What is the role of TIDs and TADs
4. How does the longitudinal difference in the neutral wind magnitude and direction affect longitudinal structure and scintillation
5. How does the coupling between lower atmosphere and ionosphere (possibly source for non-migrating tides and localized gravity wave activity) contribute and affect TEC and scintillation

## **Origins, Acceleration and Evolution of the Solar Wind**

### **Target Description:**

The supersonic, super-Alfvénic solar wind arises from the million-Kelvin solar corona, where the heating processes generating these temperatures and the role of small-scale waves, turbulence and field dynamics are far from being understood. In-situ solar wind turbulence observations show a dissipation range, which is direct evidence of ongoing turbulent heating believed to operate throughout the heliosphere, from the low corona out to the heliosheath. Subsurface solar convection powers all its mass loss, generates magnetic fields, excites solar flares through magnetic reconnection, and drives coronal mass ejections, Alfvénic waves, ion-cyclotron waves, and the various turbulent processes that evolve throughout the heliosphere. Understanding the origin, acceleration and evolution of the solar wind is critical for predicting virtually all forms of space weather. This FST directly relates to SSA-0, which focuses on physics-based understanding enabling forecast capabilities of the variability of solar magnetic fields and particles.

This FST covers the array of physical processes involved in the solar wind's origin and evolution: the sources of different solar wind types and their connection to different coronal structures; the micro-physics of particle velocity distribution functions, their anisotropies and nonthermal characteristics; the role of turbulence and wave-particle interactions in heating and acceleration; and the energization driven by structures, such as shocks, current sheets and/or magnetic reconnection.

Research included in this FST addresses the following questions: What specific observables can be derived from and used to test solar wind models? What existing observations can be used to validate solar wind models, ranging from the kinetic to the AU scales? Furthermore, in preparation for the next decade of inner heliospheric and coronal exploration with Solar Orbiter and Solar Probe Plus, what fundamental observations should drive theoretical developments?

### **Goals and Measures of Success:**

**The goal of this FST is to advance our understanding of the origin, acceleration and evolution of the solar wind for future predictive models.**

A key component of this FST will be the intercomparison and testing of competing solar wind models, better constraining them using an array of solar wind in-situ and remote sensing observations, and the development of observational metrics to evaluate their strengths and limitations. The outcome will improve solar wind modeling capabilities. Direct observations across a range of temporal and/or spatial scales will be used to determine how:

- large-scale features evolve in the origins of solar wind
- magnetic scales couple to enable the release of material that form the wind
- plasma turbulence evolves and dissipates to heat and accelerate solar wind plasma
- energy propagates across different regions of the corona and through the transition region
- charge-states and elemental abundances are set
- nano-flares and magnetic reconnection transfer stored electromagnetic energy to particles

- the solar wind plasma is heated and accelerated in the low corona

Future observations will likely transform our understanding of the origins and acceleration of the solar wind. In preparation, it is essential that we as a community define the models to be tested and establish the specific metrics used to discriminate between them. *This will allow future predictive models to be developed and tested efficiently as new observations of the solar wind emerge.*

### **Types of Investigations:**

The nature of this research effort requires the interdisciplinary combination of observational, theoretical, and numerical studies, including the following subtopics:

- waves, turbulence, and/or structures and their role in the heating of the solar wind plasma
- reconnection as an energy source that drives and/or heats the solar wind
- electron transport and heat conduction
- minor ions and their role in the origin and the evolution of the solar wind
- non-Maxwellian velocity distribution functions and their role in non-equilibrium solar wind thermodynamics
- small-scale energy release processes (nano-flares, etc.) and their role in the origin of the solar wind
- solar wind source models based on charge state and elemental composition
- mass flux, solar wind power, and their relationship to the large-scale magnetic field and small-scale dynamics
- differential studies of the spectrum of solar wind types that arise from different global-scale magnetic topologies
- evolution of solar wind properties through the solar cycle

Studies within this program will combine theoretical, numerical, and observational methods. The successful outcome of each research effort will rely on high-quality data analyses from past and present missions – such as Helios 1 and 2, Wind, ACE, Ulysses, STEREO, SOHO, SDO, IRIS, DISCOVER, etc. – to facilitate the robust comparison and constrain models with measurements. The effort could also rely on high-performance computing to facilitate multi-scale modeling activities.

### **Focus on Enabling Predictability and Interaction with User Communities:**

The driving motivation of this FST is to advance our understanding of the origins, acceleration and evolution of the solar wind with a goal to identify observational metrics that test solar wind models and to develop the understanding needed to advance predictive solar wind models. The FST should demonstrate how the expected advances will be relevant for prediction of solar wind properties.

Individual proposals should identify how they will contribute to the FST and aid with the development of predictive understanding, observationally based metrics and model validation. Proposed investigations should outline the methodologies that enable the proposed goals, with data sources and metrics (to be) used to monitor their progress. The complete FST team should

synthesize and categorize results into a list of successes and failures of solar wind models (physical, numerical, empirical or integrated) with respect to the observational metrics and specific validation tests that are generated across the team.

## **Ion Circulation and Effects on the Magnetosphere and Magnetosphere - Ionosphere Coupling**

### **Target Description:**

Accurate knowledge and understanding of the magnetospheric composition is critical for understanding the space environment. Heavy ions of ionospheric origin become a substantial constituent of the ring current and plasma sheet during storms. In large storms O<sup>+</sup> can even dominate the ring current energy density. Heavy ions therefore play a key role in the electrical currents and magnetic field structure of the entire inner magnetosphere. Heavy ions also affect the radiation belt population by controlling the growth and interaction of radiation belt particles with EMIC waves. O<sup>+</sup> may also affect the global Solar Wind – Magnetosphere coupling by quenching dayside reconnection rates as well as global magnetospheric convection, and on the night side affecting location and recurrence of reconnection and associated instabilities. Thus the heavy ion composition, and in particular O<sup>+</sup>, plays an important role in understanding geomagnetic variability (SSA-1) and the radiation environment (SSA-6).

Understanding and modeling of the magnetospheric composition and all of the associated feedback mechanisms is an extremely challenging task, and an important issue for space weather models. While some progress has been achieved in understanding how O<sup>+</sup> is energized and transported from the central plasma sheet to the ring current, there is a gap in our understanding of the source and transport mechanisms in the ionosphere and to the magnetosphere largely as a result of the complex interplay between the solar wind, magnetospheric activity and the ionosphere. Mechanisms include transport of ionospheric material from mid- to high-latitudes, potentially through the cusp region and polar cap, cusp outflow stimulated by precipitation and poynting flux (in turn stimulated by solar wind variability), outflow from the auroral regions, outflow directly from sub-auroral latitudes leading to the warm plasmaspheric cloak.

This topic focuses on how and when ions, and in particular O<sup>+</sup>, are supplied from the ionosphere to the magnetosphere and where it becomes available for energization. Newly available data from the Van Allen Probes and MMS satellites as well as older data sets such as Cluster and DMSP sampling both inner and outer magnetosphere, and covering eV to MeV energies provides an unprecedented opportunity to determine the accumulation and energization processes of O<sup>+</sup> ions throughout the magnetosphere during geomagnetic storms. A number of other currently-operating spacecraft, as well as new missions soon to launch, support these topics as well, forming a comprehensive suite of observations that can support studies of conductivity, as well as (in many cases) interhemispheric effects. In addition, global models and computational capabilities have reached the level of maturity allowing taking full advantage of the available data.

### **Goals and Measures of Success:**

**The goal of this FST is to understand how heavy ions, and in particular O<sup>+</sup> ions, are energized transported from the ionosphere to the magnetosphere where they become available for further energization up to ring current energies.**

Proposals to this FST should aim to determine heavy ion characteristics in the magnetosphere across a wide range of L-shells/geomagnetic latitudes, including the inner magnetosphere that

will allow one to identify and differentiate various ionospheric source regions, such as plasmaspheric cloak, auroral outflow, and cusp outflow; identification of what controls heavy ion characteristics in the ionosphere and magnetosphere; identification of the important sources and transport processes including through through wave-particle interactions.

**Types of Investigations:**

As there is currently an FST which is dedicated to a portion of this topic considering how O<sup>+</sup> is energized and transported through the transition region from the plasma sheet to the ring current, proposed investigations should focus on other aspects of the heavy ion circulation throughout the magnetosphere while being aware of, incorporate, and work with the currently funded FST. Suggested types of investigations include:

- Data analysis seeking to characterize ionospheric and magnetospheric processes that directly or indirectly are critical for the supply of O<sup>+</sup> to the magnetosphere. This includes their dependence on solar and solar wind drivers, seasonal changes, and magnetospheric drivers including wave-particle interactions.
- Data analysis that seeks to characterize the spatial and temporal distribution of O<sup>+</sup> in the inner magnetosphere to the outer magnetosphere.
- Modeling seeking to understand and confirm the physical mechanisms that directly or indirectly are critical for the supply of O<sup>+</sup> to the magnetosphere.

**Focus on Enabling Predictability and Interaction with User Communities:**

An important component of the FST is to demonstrate relevance to user needs. Individual proposals should identify how they will contribute to the FST and improve magnetic data that can eventually be used in user/operational mode



## **Toward a Systems Approach to Energetic Particle Acceleration and Transport on the Sun and in the Heliosphere**

### **Target Description:**

An understanding of the acceleration and transport of energetic electrons and ions on the Sun (Solar Energetic Particles, or SEPs) and in the heliosphere is central to predicting and mitigating space weather threats and advancing human exploration of space. While flare acceleration mechanisms on the Sun and coronal mass ejection (CME) driven shock acceleration mechanisms in the heliosphere have been studied for many years, possible relationships between the two have only been appreciated relatively recently. For example, shocks may be present in flares due to reconnection outflows; and flares may play a role in high-energy SEP events, in contrast to the more widely-held view that large gradual SEP events are dominated by shocks at all energies. It has also been recognized that the coupling between flare acceleration and CME-shock acceleration is not one-way: recent high-sensitivity observations by *Fermi* revealed gamma-rays associated with flares occurring up to ~40 degrees behind the solar limb and gamma-ray emission long after the flare X-ray and EUV emissions have subsided. Both revive the idea that CME-shock accelerated particles traveling back to the Sun may produce gamma-rays.

The exact physical relationship and relative importance of flare acceleration and CME-shock acceleration remain controversial. Nevertheless, significant progress has been made in understanding flare physics, CME shocks, and shock acceleration thanks to missions flown over the past decade - including RHESSI, Fermi, TRACE, SDO, SOHO, ACE, and STEREO – as well as progress on theoretical understanding. With anticipation growing for the *Solar Probe Plus* and *Solar Orbiter* missions it is appropriate and necessary to take a systems approach to the problem of solar energetic particle acceleration and transport as a means of advancing physics-based models and developing predictive capabilities.

The strategic science area “Physics-based Solar Energetic Particle Forecasting Capability” (SSA-3) requires a fundamental understanding of the acceleration and transport of solar energetic particles. This FST aims to advance this understanding through observational, theoretical, and modeling initiatives that result in improved understanding of the relevant mechanisms, data products that may be assimilated into models, and models that improve the predictability of the timing and origin of SEPs, ultimately informing SSA-6 (“Physics-based Radiation Environment Forecasting Capability”).

### **Goals and Measures of Success:**

**The goal of this FST is to take a systems approach to understanding the acceleration and transport of solar energetic particles.** The investigations addressing this FST will, as a whole, use a systems approach to integrate investigations covering the different acceleration regions of SEPs from active regions to the corona and through the heliosphere. These include the need to

- develop a detailed observational understanding of the properties of the source regions of solar energetic particles;
- understand the composition and evolution of solar energetic particle populations in time and space;

- identify the mechanisms by which impulsive energetic particle events or gradual events of large angular extent occur;
- understand the relative roles of flares and CMEs in producing energetic particles as well as the underlying acceleration mechanisms;
- understand the origin and distribution of seed particles;
- develop advanced systems-based models of the production and transport of solar energetic particles as precursors to predictive capabilities.

Investigations based on observational, theoretical, and/or modeling initiatives are expected to show clearly how they contribute to a broader understanding of the coupled physical processes that underpin the production and transport of solar energetic particles. Observational investigations should show how new methods or techniques will yield insights into the production and transport of energetic particles, and/or how they will lead to data or data products that may be assimilated by models. Theoretical investigations should lead to an understanding of the comparative importance of the coupled physical processes that contribute to the acceleration and transport of solar energetic particles. Modeling efforts should leverage progress in observations and theory to demonstrably improve our understanding of the timing, origin, and properties of solar energetic particles and their potential for affecting the near-Earth environment.

#### **Types of Investigation:**

- Determination of the relative importance of various particle acceleration mechanisms (e.g., magnetic reconnection, turbulence, and shocks), and particle transport mechanisms, in different physical scenarios.
- Comparative studies of particle populations on the Sun inferred from their electromagnetic radiations and/or those detected in-situ.
- Determination of the origin and distribution of seed populations of SEPS, and investigation of the relative importance of contributions to the seed populations of SEPs, such as flare-accelerated particles escaping the Sun and/or relics of a previous CME.
- Investigation of CME evolution and shock formation/evolution and/or flare initiation and evolution in order to determine conditions leading to acceleration of SEPs.
- Investigation of the relative roles of flares and CME-driven shocks in the acceleration of energetic particles, as well as temporally and spatially extended gamma-ray events.
- Determination of the distribution of spectral and isotopic characteristics of SEPs, and characterization of the underlying causes for the distinction between highly impulsive and gradual SEP events.

#### **Focus on Enabling Predictability and Interaction with User Communities:**

An important component of the FST is to demonstrate relevance 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 of a predictive capability.

# Coupling Between Different Plasma Populations by Means of Waves within the Magnetosphere

## Target Description:

Plasma populations in the Earth's space environment habitually affects human assets within that space. Quantification of satellite surface charging requires a detailed knowledge of the background plasma density and fluxes of ring current ions and electrons, while deep dielectric charging is produced by the radiation belt electrons. Plasma waves play a very important role in the dynamics of different magnetospheric plasma populations. Ultra Low Frequency (ULF) waves are responsible for the radial diffusive transport, Very Low Frequency (VLF) and Extremely Low Frequency (ELF) waves inside the plasmasphere provide pitch angle scattering and loss of particles and VLF waves outside of the plasmasphere can provide both loss of particles due to pitch angle scattering and acceleration due to energy diffusion. Waves also provide mechanisms by which different plasma populations can interact with each other. For example, ring current particles generate Electromagnetic Ion Cyclotron (EMIC) and chorus waves that affect the dynamics of the radiation belt electrons. Background plasma density and ion composition play an important role in modulating the generation of waves and wave-particle interactions. High-fidelity multi-point in-situ measurements of the magnetic and electric fields, electron and ion fluxes, and ion composition from the Van Allen Probes, MMS, THEMIS, and Cluster spacecraft, amongst other resources, provide a unique and timely opportunity to quantify the significance of each mechanism as a function of solar wind and geomagnetic conditions. This FST is most relevant to SSA-0 (Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and Inputs to Earth's Atmosphere), SSA-1 (Geomagnetic Variability), and SSA-6 (Radiation Environment).

## Goals and Measures of Success:

Plasma waves play an important role in the dynamics of various inner magnetospheric plasma populations. **The main goal of this investigation is to understand and quantify how different plasma populations (including thermal plasmas, the ring current, heavy ions, and radiation belt electrons) influence each other in the magnetosphere and how waves influence and facilitate this process.** This investigation will help quantify the dynamic evolution of different particle populations and will improve the forecasting capabilities of current and future computational models. This topic will help us understand particle dynamics in the inner magnetosphere and how different particle populations can affect each other by means of waves. The advances made by this FST may feed into future comprehensive models of the inner magnetosphere. Measures of success will be any comprehensive data analysis results that can improve our understanding and/or improve models with quantifiably better prediction of plasma fluxes in Geospace.

## Types of Investigations:

The types of investigation that would be appropriate for this focused topic include:

- Comprehensive analysis of a variety of available observations, including both space and ground data, into the properties of plasma and wave populations in Geospace and the effects of their coupling.
- Development/improvement of empirical models for plasma population dynamics.
- Development/improvement of empirical models of ULF, VLF, and ELF waves.

- Theoretical studies of wave-particle interactions.
- Modeling studies combining the dynamics of various plasma populations coupled by means of wave-particle interactions.
- Validation of the models and theoretical predictions via comparison with multipoint in-situ observations of the dynamics of plasma populations.

## **Probabilistic Forecasting and Physical Understanding of Extreme Events**

### **Target Description:**

Strategic Science Area SSA-0 focuses on physics-based understanding enabling forecast capabilities for the events driven by the variability of solar magnetic fields. All strategic science areas rely in some way on the development of predictive understanding emerging from SSA-0. Extreme solar events introduce significant potential hazards associated with abrupt increases in solar energetic particle radiation and geospace superstorms. Rarely occurring extreme 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 events can damage satellites and avionics. Extreme 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 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 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 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 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.

### **Goals and Measures of Success:**

The goals of this FST are twofold: to develop models of extreme events, and to test these models via comparison to satellite and historic data. Measures of success are (1) the development of metrics to test or quantify the success of extreme event models, (2) the development of observational precursors that can be used to quantify potential development of extreme events, (3) the development of methodologies for probabilistic forecasting, and (4) the examination of historic datasets that can be used to assess extreme events that may have occurred in the past.

### **Types of Investigations:**

- Studies that use historical records (ice core  $^{10}\text{Be}$  and  $^{36}\text{Cl}$  data,  $^{14}\text{C}$  in tree rings) and satellite data to identify extreme events for comparison with results of models.
- Numerical models to understand physical origins of extreme 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 .

**Focus on Enabling Predictability and Interaction with User Communities:**

The driving motivation of this FST is to advance substantially our physical understanding of extreme 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) .

## **Understanding Physical Processes in the Magnetosphere--Ionosphere / Thermosphere / Mesosphere System during Extreme Events**

### **Target Description:**

Detailed observations of heliospheric processes during superstorms are rather limited, and statistics is sparse. Superstorms are unusually strong storms where the Dst index reaches below 300 nT and even below 500 nT in extremely rare circumstances. Evidence that geomagnetic storms can potentially be much stronger than that observed during the space age comes from historical observations of the solar storm in 1859, known as the Carrington event, and recent observations of the very powerful Coronal Mass Ejections (CME) that occurred in July 2012, that largely missed the Earth. Understanding the effects of superstorms and the strongest (e.g., 1 in 100 years) space weather events is a key component of the National Space Weather Action Plan. Such an understanding is required to develop mitigation strategies for worst case Geomagnetically Induced Currents (GIC), spacecraft charging, communication outages and navigation error scenarios. Understanding the coupling processes that occur under extreme conditions presents a challenge, as these processes may be very different than those under the more typical conditions for which existing physics-based models were developed. Saturation processes or nonlinear responses of the systems during extreme driving may preclude extending empirical parameterizations to the more extreme values for drivers that occur during such events. Using available observations of superstorms and historical records of extreme events, this FST will conduct focused investigations of key physical processes needed to extend modeling capabilities to the conditions that occur during extreme events. This proposed topic is relevant to nearly all of the Strategic Science Areas (SSAs).

### **Goals and Measures of success:**

**The goal of this focused topic is to identify the key physical processes that differentiate superstorms from more typical storms by using any and all available observations of superstorms and historical records of extreme events, so that modeling capabilities can be accurately extended to extreme events.** The efforts of this FTS will be targeted at filling critical gaps in our understanding of the Geospace System dynamics that occur during extreme events. This FST will improve our ability to model superstorms and Carrington-type storms and improve our ability to predict the consequences of the extreme events. The advances made by this FST may feed into a future long-term strategic capability topic on the integrated magnetospheric response to superstorms. Successful investigations will provide quantifiable evidence of progress toward accurate simulation of extreme Space Weather events and their effects in Geospace.

### **Types of investigations:**

Types of investigations appropriate for this focused topic include:

Theoretical and modeling studies focused on understanding the physics of solar wind-magnetosphere interaction changes from normal times to superstorms/extreme events (e.g. boundaries, currents, properties of plasma populations, etc).

Multipoint and multi-instrument observations of superstorms.

Studies concerning the response of currents, radiation belt particle fluxes, and magnetospheric electric and magnetic fields to extreme driving.

Quantifying the limitations of current models in simulating responses (e.g., saturation effects, balance between currents and plasma, topology, etc. )

Development of the data-driven models and analysis of the response of the geospace system to extreme driving.

Development and validation of simulations that can accurately represent the extreme responses that occur in the magnetosphere and ionosphere during superstorms and Carrington-type storms.

Application of the extreme value theory to understand the extreme behavior of heliophysics systems and making predictions.



## **Understanding the Impact of Thermospheric Structure and Dynamics on Orbital Drag**

### **Target Description:**

Operators of Low Earth Orbit (LEO) spacecraft face a continuing operational challenge due to variable atmospheric expansions and contractions. These produce non-constant drag forces on a spacecraft that alter its attitude and orbit. The satellite drag force is dependent on a number of factors, including the atmospheric density, the ballistic coefficient, and the relative speed of the satellite within the atmosphere. LEO situational awareness requires continuous precise orbit determination, conjunction assessment, and collision avoidance 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. In LEO, atmospheric drag is the largest contributor to errors in orbit determination and is associated with problems related to satellite tracking, collision avoidance, and re-entry prediction. Thus, improved estimates of atmospheric drag on LEO spacecraft and space objects will positively impact the operations and performance of these critical space assets. 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, most of the geospace energy input to the atmosphere during storms comes through high latitudes with significant mesoscale structure and 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 mesoscale heating or not, especially during the main phase of geomagnetic storms.

The effect of atmospheric composition also needs to be investigated and quantified, particularly during non-storm and quiet time periods. The increase of carbon dioxide in the lower thermosphere, for example, appears to cause a cooler thermosphere during solar minimum conditions, thus contributing to thermospheric collapse with decreasing density and resulting in the increased lifetime of orbiting debris. Understanding thermospheric composition changes is crucial to predicting negative ionospheric storm effects and points to the need for better atmospheric density and wind models, especially during geomagnetic storm periods.

This focused topic is seeking focused investigations that will quantify storm-time uncertainties of neutral density and winds and investigations that seek to understand the physical causes of such uncertainties so that they can be better simulated and predicted. It is directly aligned with SSA-2: Physics Based Satellite Drag Forecasting Capability. While empirical thermospheric density models are used by operational systems, since they currently outperform physics-based models, it is understood that improvements in both current epoch specification and prediction will primarily come from a physics-based understanding of the density that is well-modeled and constrained with data, including with data assimilation techniques.

## Goals and measures of success

**This topic aims to further the understanding of the physical causes for geomagnetic storm-time variability in the main atmospheric parameters (mass density and winds) that are the primary contributors to atmospheric drag and better quantify their uncertainty during storm times.** Through identifying the mechanisms that can drive density and wind changes and improving their characterization, this will improve drag specification and prediction. An improvement to models, both empirical and physics-based, as well as data assimilative techniques that reduces the uncertainty in geomagnetic storm-time variability of neutral density and winds while using existing and new datasets, is the key measure of success for this FST. Successful investigations will quantify density and wind uncertainties during storms in higher time cadence and explore mesoscale dependence of that response during storms. Investigations will also quantify improvements in density and wind uncertainty, where appropriate. This topic supports topic SSA-2 (Satellite Drag).

## Types of investigations:

This FST seeks investigations that will use existing datasets to reduce the uncertainty of modeled atmospheric density and wind changes that leads to orbital drag uncertainties.

- Improvements are needed in understanding the processes creating small and meso-scale density structures and localized thermospheric heating.
- An important contribution to better density prediction is the accurate modeling of the timescales for increasingly severe density changes due to initiating and evolving storms as well as timescales of atmospheric relaxation back to quiet conditions after storm periods.
- These timescales can be on the order of minutes to days.
- Cooling rates of the heated thermosphere based on composition changes and wind dynamics could be explored and improved.
- Empirical and physics-based model results need to be compared and validated by observations.
- Coupled models and data assimilation schemes could be considered, compared and validated.
- This FST does not provide for the development of new models since the ultimate goal is to clarify our present understanding as well as to identify the gaps in our existing understanding that can ultimately improve specification and forecasting capabilities. However, funding for key small improvements of models and techniques can be requested to aid the analysis.
- Connections between models, and observations, data assimilation methodologies, and high-performance computing all play relevant roles for improving satellite orbit determination.
- Investigations related to magnetosphere-ionosphere-thermosphere coupling, atmospheric and ionospheric disturbances during geomagnetic storms, meso and small-scale structuring, all contribute to this topic.

## **Solar Magnetic Inputs to Coronal and Heliospheric Models**

### **Target Description:**

One of the primary goals of the LWS program is to achieve a quantitative understanding of how the Sun influences the Earth's magnetic environment. A key aspect of understanding this interaction is the ability to quantitatively describe – and ultimately predict - the global solar corona and inner heliosphere. 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), SSA-1 (Geomagnetic Variability), SSA-3 (Solar Energetic Particle), and SSA-6 (Radiation Environment). A crucial input to models of the global solar corona and of the solar wind, whether they be empirical or physics-based, is the magnetic field near the solar surface. Models frequently use synoptic magnetic maps, which are built up from individual full-disk photospheric magnetograms taken over the course of a solar rotation. These synoptic maps can be developed from a number of ground- and space-based observatories, including, but not limited to: GONG, SOLIS, MDI, and HMI. Future investigations, including FASR, COSMO, *Solar Probe Plus* (SPP), and *Solar Orbiter* will provide even richer, more complex measurements in the near future.

Current global models of the solar corona and inner heliosphere are driven by such observations, but are severely hampered by limitations of the observations and in the analysis of these observations. In particular, synoptic maps suffer from a number of problems and limitations. First, they are not “synchronic” maps, that is, instantaneous snapshots of the global photospheric field at one time, which is what the global models require. Second, these maps often differ substantially from one observatory to the next and accurate inter-calibration is complicated. Third, the polar regions, which make a significant contribution to the open flux observed in the heliosphere, are seasonally obscured and poorly – if at all – observed. Fourth, differential rotation effects are only sometimes incorporated, and then, not systematically from one observatory to the next. Fifth, line-of-sight magnetograms (rather than the potentially available vector measurements) are used to reconstruct the radial photospheric field. Finally, as the magnetic field is not force free at photospheric heights, photospheric vector magnetograms are sometimes “preprocessed” to enable force-free extrapolation. Ideally, time sequences of global maps that smoothly assimilate new data (including far-side measurements) would be available to drive global models and provide a real-time forecast of the state of the heliosphere.

With the availability of almost six years' worth of full disk vector magnetograms at high time cadence from the HMI instrument on board SDO and the launch of SPP in two years, a rigorous assessment of the use of magnetograms and magnetic maps in quantitative models of the corona and solar wind is both timely and necessary. To make a significant breakthrough, however, will require a team approach, including magnetic field observers, flux-evolution modelers, and corona/solar wind modelers.

### **Goals and Measures of Success:**

**The goal of this focus team will be to develop new techniques and methods that will enable advances in our quantitative predictions of the global state of the solar corona and of the solar wind parameters (e.g., solar wind speed, IMF polarity, open magnetic flux, plasma parameters, etc.) based on solar magnetic field measurements.** While the assessment

/analysis of individual magnetograms would be an appropriate component of this effort, the focus would be on the production of the most accurate maps of the Sun's global magnetic field (as opposed to, say, the surface magnetic field in an active region). Measures of success would be:

- A standard inter-calibration for photospheric magnetic maps from different sources.
- Accurate estimates of the Sun's polar magnetic fields during different seasons and parts of the solar cycle.
- The ability to characterize the photospheric magnetic field on the Sun as a function of time.
- Improvements to the accuracy of coronal and solar wind models for both real time descriptions and for forecasts.
- Validation of models by quantitative comparisons with chromospheric and coronal magnetic field measurements.

**Types of investigations:**

- Studies that quantitatively calibrate magnetograms from NASA missions (e.g., SOHO/MDI and SDO/HMI) with measurements from ground-based observatories or other validation studies, to obtain a best estimate of the Sun's magnetic field.
- Studies that quantitatively characterize and assess the accuracy of different techniques for producing photospheric magnetic maps, including estimates of the Sun's polar magnetic field and the use of synchronic or synoptic maps.
- Studies that use vector magnetograph data to improve the estimate of the Sun's global magnetic field.
- Studies that quantitatively describe the evolution of the Sun's surface magnetic field via flux evolution models which, for example, assimilate new magnetograms into real-time descriptions of the state of Sun's magnetic field, incorporate estimates of the Sun's field from far-side images, and / or incorporate differential rotation and dispersion into predictive models of this evolution.
- Studies that quantitatively assess the impact of extrapolation techniques (e.g., potential versus nonlinear-force-free versus magnetohydrodynamical) on our ability to model observed coronal structures and the observed temporal evolution of the solar wind.
- Studies that develop techniques for making quantitative measurements of chromospheric or coronal magnetic fields which can be readily assimilated into, and thereby improve, solar magnetic field models.

**Focus on Enabling Predictability and Interaction with User Communities:**

Measurements of the Sun's global magnetic field are presently the primary data input for background models of the solar wind, for example those used at NOAA SWPC and the CCMC. Individual proposals should identify how they will contribute to the FST and improve magnetic data that can eventually be used in user/operational mode

# **Understanding the Response of Magnetospheric Plasma Populations to Solar Wind Structures**

## **Target Description:**

Plasma populations govern space weather conditions within the Earth's magnetosphere. Energetic particles cause single-event upsets and deep dielectric charging in spacecraft electronics and may be harmful to humans in space. While we understand that magnetospheric dynamics is driven by the solar wind, we only understand the first order responses of the magnetospheric populations. Their nonlinear response to different driving conditions, involving coupling and feedback between populations, magnetosphere and ionosphere, wave particle interactions is still poorly quantified. Many aspects of current geospace modeling efforts rely on simple parameterizations and do not take into account the complexities of different solar wind drivers, or even more the timescales for geoeffective coupling, or the combined effect of multiple driving parameters that can result in dramatically different responses from those to individual drivers. Solar wind can change the locations of the magnetopause and plasmapause, can change the configuration of the global magnetic and electric fields and can drive the generation of Ultra Low Frequency, Very Low Frequency, and Extremely Low Frequency waves that can interact with particles. Understanding and predicting when and where radiation effects related to space weather may occur requires detailed knowledge of the how particle radiation is driven by the solar wind. This topic is well suited to make significant advances in our understanding of low-to-high energy particle dynamics, and hence will lead to next-generation modeling and forecasting models - important for effective mitigation of geomagnetic storms.

This FST is relevant to LWS TR&T Strategic Science Areas (SSA's): SSA-0: Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth's atmosphere; SSA-1: Geomagnetic Variability; and SSA-6: Radiation Environment.

## **Goals and Measures of Success:**

**This FST is targeted at improving our understanding of how particular structures in the solar wind affect global fields and particle populations from a whole systems approach.**

Measures of success will include the following:

- Improved empirical models for the magnetospheric plasma environment as a function of solar wind and geomagnetic conditions.
- Improved first principle models capable of predicting the time-dependent response of magnetospheric plasma populations to varying solar wind conditions.
- Validation of the models, and specification of intrinsic errors during selected extreme events.

## **Types of Investigations:**

Development of the quantitative models for magnetospheric plasma populations demands the coordinated research of investigators with access to multipoint ground-based and spacecraft observations of magnetospheric and solar wind conditions, as well as global numerical

simulations. Investigations will focus on understanding how particular structures in the solar wind determine the spatial and temporal evolution of the magnetospheric plasma populations. Illustrative case studies, empirical models, investigations involving machine learning, and the development of global simulations capable of assimilating both in situ and remote observations are encouraged.

# Heliospheric and Magnetospheric Energetic Precipitation to the Atmosphere and Its Consequences

## Target Description:

Energetic particle precipitation, both magnetospheric and solar in origin, has a significant impact on the coupled magnetosphere-ionosphere system, while also impacting the mesosphere - lower thermosphere domain. In recent years, we have significantly improved our understanding of the acceleration mechanisms of energetic particles, however loss mechanisms and their effects on the atmosphere and ionosphere remain poorly understood. Electron precipitation above  $\sim$ keV and proton precipitation above  $\sim$ 100 keV ionize the D and lower E regions of the ionosphere and contribute directly and indirectly to the production of NO<sub>x</sub> and HO<sub>x</sub> constituents in the upper atmosphere. The ionization, complicated chemistry, and precise effects of these products is nuanced. One difficulty in understanding and projecting the future states of the atmosphere comes from our inability to identify and isolate the signals from external forcing and different feedback processes. These feedback processes include the effects from the Sun on the intermediate region of the mesosphere, lower thermosphere, and lower atmosphere and from the particle precipitation on these regions back to the magnetosphere. But before we can look at these higher order effects we first need to better understand, quantify and ultimately forecast the spatiotemporal dynamics and input energy spectra that impact the atmosphere. The aggregate energy input into the Magnetosphere-Ionosphere-Thermosphere system is not known at this point, nor is it known how this varies with latitude and longitude, with geomagnetic activity, or with solar cycle. This science topic can be investigated comprehensively using both space- and ground-based measurements or kinetic modelling. How heliospheric and magnetospheric energetic particles impact the ionosphere-atmosphere system is still a vast open question in the field, and this final portion of the full Sun-Earth system is key to understanding the entire energy pathway leading to advancing the knowledge relevant to SSA-0 (direct headway can be made on this topic by quantifying the precipitating flux and utilizing the current and future measurements to discern the effect this precipitation has on the atmosphere), SSA-2 (as the high-energy end of this spectrum, which can affect satellite drag, has not been sufficiently investigated in the past), SSA-3 (addressing SEPs directly, in the context of SEP direct access to Earth's atmosphere, particularly in the polar cap), and SSA-6 ( by directly studying the precipitating component of the radiation environment, and employ modeling methods to determine the effects on the atmosphere directly.) With observations from Van Allen Probes, the upcoming ERG mission, an increasing number of CubeSat and SmallSat as well as many previous missions focusing on measuring precipitating fluxes, and the wealth of ground based data sets and current modeling efforts, now is arguably the best chance we have to bring closure to this science topic.

## Goals and Measures of Success:

**The primary goal of this FST is to quantify what the long- and short-term variations and characteristics are in the energetic particle precipitating flux and energy spectrum and their impact in the Earth's atmosphere.** This FST should lead to a better understanding of how these precipitation events are affected by geomagnetic activity and solar cycle, ultimately leading to understanding and forecasting of the region affected by this ionization, provide inputs to

atmospheric chemistry models, determine the size and temporal scales of the regions affected, as well as how this changes with the intensity level of particle precipitation.

### **Types of Investigations:**

- Theoretical, empirical, and modelling studies focused on predicting particle precipitation to the atmosphere including the temporal variations, spatial scale size, and precipitation energy spectra.
- Multipoint and multi-instrument observations of particle precipitation during periods of geomagnetic activity specifically looking at the precipitated energy spectra and flux as well as the MLT - L or equivalently the Latitudinal and longitudinal extend of the precipitation.
- Development and validation of simulations that can accurately represent particle precipitation to the atmosphere and its dependence on geomagnetic activity.
- Studies which consider the relative importance of different loss mechanisms to the upper atmosphere.
- Theoretical, empirical, and modelling studies focused on quantifying the sensitivity of the atmospheric response to particle precipitation.

### **Focus on Enabling Predictability and Interaction with User Communities:**

An important component of the FST is to demonstrate relevance to user needs. For example, results from these studies may be able to contribute to updated EPP energy spectra and variation into the atmospheric coupling models such as WACCM. Individual proposals should identify how they will contribute to the FST and improve magnetic data that can eventually be used in user/operational mode.



## Understanding the Onset of Major Solar Eruptions

### Target Description:

The LWS program has the overarching goal to achieve a quantitative understanding of how the Sun influences the Earth's environment. A key aspect of understanding this interaction is the ability to quantitatively describe – and ultimately predict - the occurrence of major solar eruptions. This proposed topic is essential to nearly all of the LWS Strategic Science Areas (SSAs). For example, Solar Energetic Particle (SEP) events (SSA-3) generated by flares and Coronal Mass Ejections (SSA-0) increase radiation hazards throughout the solar system and adversely impact our space- and ground-based assets (SSA-1). The initial particles can arrive in minutes to hours after an eruption on the Sun.

A key difficulty in achieving the goals of SSA-3 (probabilistic prediction of the spectral intensity of SEP events, and increased time periods for all-clear forecasts) is forecasting the likelihood of a major eruption from active region(s) on the Sun, hours to days prior to the event. Present-day forecasts are empirical. For example, NOAA/SWPC currently relies on qualitative assessments of sunspot groups to produce a 24, 48, and 72 hour forecasts. There are statistical methods that could potentially improve these forecasts based on characterization of prior flaring, surface solar magnetic field properties derived from magnetograms, etc. However, even such techniques typically have little theoretical or modeling insight incorporated into their methodologies.

There has been significant theoretical, modeling and observational work on the eruptive properties of solar magnetic fields, as evidenced by previous LWS Focused Science Teams (FSTs). However, it appears we are still many years away from an entirely first principles approach for predicting major eruptions. **The goal of this FST is to directly combine insights from theory, modeling, and observations to improve probabilistic forecasts of major solar eruptions required by the user community.**

### Goals and Measures of Success:

The goal of this science topic will be to obtain a quantitative understanding of the signatures which indicate the imminent occurrence of a major solar eruption, such as magnetic flux emergence, the interaction of the emerging flux with existing structures, and the degree of non-potentiality in the atmosphere. This requires studies of local and global-scale phenomena as ably demonstrated by the observations of the Solar Dynamics Observatory over the past six years. Measures of success would be:

- The ability to integrate numerical and observational studies across the breadth of temporal and spatial scales to better understand major eruptions.
- The ability to differentiate between minor and major storm eruptions.
- The ability to robustly determine “all-clear” periods for major eruptions.
- Production of critical derived data products such as Poynting flux, helicity flux injection, and free energy build up from the observables with appropriate estimates of uncertainties.
- Identification of comprehensive, consistent, robust extrapolation methods involving magnetic field measurements in photosphere, chromosphere and corona to identify degrees of non-potentiality and the timescales on which it develops.
- The ability to predict the location, timing, and initial velocity of major solar eruptions.

### **Types of investigations:**

- Studies (Observational, theoretical, empirical, statistical and/or modeling) that identify signatures of stability and/or imminent eruption triggering and onset.
- Studies which use these signatures to provide probabilistic forecasts of major solar eruptions:
  - Studies of the processes by which the emergence of magnetic flux energizes pre-eruptive active regions and / or triggers eruptions.
  - Studies that quantify the flux of magnetic energy stored, entering, or leaving solar active regions, and study how this relates to the triggering of eruptions.
- Studies that identify signatures of stability and/or imminent eruption.
  - Studies of magnetic reconnection onset or other destabilization mechanisms, as related to eruption onset, throughout the solar atmosphere and across the broad range of scales presented therein.
  - Studies that relate inferred/measured quantities such as free magnetic energy, non-potentiality, helicity flux injection, and Poynting flux injection to the likelihood of a major event.

### **Focus on Enabling Predictability and Interaction with User Communities:**

An important component of the FST is to demonstrate relevance to user needs, especially when designating storm onset, assessing all-clear periods, or differentiating between minor and major solar events. For example, an end user of this FST would be the operational group at NOAA/SWPC. Individual proposals should identify how they will contribute to the FST and improve understanding of major event onset and the physical properties of those events that can eventually be transitioned to user/operational models.

## **Understanding Ionosphere-Thermosphere (IT) responses to high-latitude processes and the coupled Magnetospheric energy input**

### **Target Description:**

The ionosphere is electro-dynamically coupled with the magnetosphere from above, but also co-located and mechanically coupled with the dense neutral atmosphere. While the major energy source for the IT system is solar EUV flux, during geomagnetically active times, like storms, magnetospheric energy input can be equally or even more important. The result can be transient but severe effects on the Earth environment, like communication and navigation disruptions, changes on orbital drag and the lifetime of LEO satellites. Magnetospheric energy input enters at high latitudes through complex, coupled processes. As a result electron density and thermospheric mass density at a given altitude are both spatially and temporally variable with magnetospheric energy input. Changes in the neutral upper atmosphere can affect a host of processes, like ion-neutral drag coupling that governs the exchange of momentum and Joule heating rates, species-dependent chemistry and recombination rates that change the electrical conductivity of the ionosphere, altitude profile of precipitation absorption and ionization that affect ionospheric conductivity and MI coupling and more. Electron density profiles and TEC are similarly affected by high-latitude energy input. There is a need to understand the causes and consequences of this thermospheric mass density and TEC variations, which are critical to Space Weather and not well captured by existing models but where data exist. There is a need to observationally establish meso-scale patterns of energy input and responses and advance the ability of models to capture the important missing physics. Better parameterizations are needed to dramatically improve our predictive capability for thermospheric density, particularly during periods of enhanced geomagnetic activity and even, though not exclusively, during extreme solar minimum conditions.

Open questions include:

- How do magnetospheric energy inputs become processed to provide local, regional, or global changes in thermospheric density, electron content and TEC. For example, what are the effects of different scale sizes in energy inputs in terms of energy budget available to the IT system?
- What are the effects of particle precipitation on the structure of ionospheric conductivity and neutral heating, including soft electron precipitation vs. Joule heating to produce cusp neutral upwelling as well as heating sources vs. conductivity sources?
- What are the variations in thermospheric composition during geomagnetically active events, including neutral Helium, and how are they driven by various energy inputs such as negative vs positive ionospheric storms?
- What are the mechanisms that drive thermospheric structure in the high latitudes, like recently shown polar latitude density enhancements during active times or localized neutral heating during compressions or near a storm onset?

**The focus of this topic is to improve the ability of models to capture the important missing physics and parameterizations needed to dramatically improve our predictive capability for total electron content (TEC), electron density profiles and thermospheric density.** This is particularly needed during periods of enhanced geomagnetic activity and even, though not exclusively, during extreme solar minimum conditions for satellite drag applications. This topic

is within the context of SSA-2: Physics-based satellite drag forecasting capability and SSA-4: Total Electron Content.

### **Goals and Measures of Success:**

**The primary goal of this FST is to promote understanding of neutral density variability, from the lower thermosphere well into the exosphere (>600 km), as well as TEC and electron density profile variability that result from high-latitude heating and cooling conditions.** Comparisons of both empirical and physics-based modeled density changes resulting from high speed streams and geomagnetic storms with existing in-situ and remotely sensed satellite density data is needed for evaluating the success of these models. Proposals should suggest metrics that can demonstrate reductions in neutral density and TEC variability uncertainty and identify application paths.

### **Types of Investigations:**

This solicitation seeks investigations that focus on the improvement of empirical and physics-based models to help resolve different scale sizes in MIT energy inputs. Types of appropriate investigations include:

- Studies that will yield improvements in ionospheric conductivity and neutral heating by understanding particle precipitation and Joule heating.
- Studies that will help understand the Magnetosphere-Ionosphere (MI) coupling processes that result in mesoscale structure of the energy input
- Investigations that can help understand thermospheric composition variations during geomagnetic storms, including changes in neutral Helium during conditions such as negative and positive ionospheric storms.
- Investigations that help understand mechanisms driving thermospheric structure in the high latitudes during geomagnetically active periods.
- Modeled densities that include the use of spectral irradiances and spectral indices beyond F10.7 and geomagnetic indices beyond Ap are encouraged.

It is anticipated that model-data comparisons will make progress towards eventual ensemble modeling and/or data assimilation techniques to improve neutral atmosphere and ionosphere forecasting.

### **Focus on Enabling Predictability and Interaction with User Communities:**

Proposals in response to this solicitation are encouraged to understand and state user requirements for drag specification improvement. NASA will facilitate interaction between selected teams and user communities that can eventually benefit from new methods for geomagnetic storm-time upper atmosphere density specification and forecasting in satellite drag applications. The use of density databases not readily available to the scientific community at the present should be explored, and processes identified, to make these types of data more widely available.

## **Enabling Geospace System Science through Imaging and Distributed Arrays**

### **Target Description:**

Our scientific understanding of the coupled global behavior of the geospace system, comprising the magnetosphere, ionosphere and thermosphere, depends significantly on global measurements provided by imagers and a distributed array of in situ measurements. The Heliophysics Decadal Survey and the National Science Foundation Portfolio Review emphasized the need for “System Science” to attain the next level in predictive understanding of the geospace system. Although the current level of system understanding has been dominated by in-situ multipoint and statistical measurements there is a wealth of global observations that hold great promise not only for understanding the large-scale evolution and causality of the solar wind-geospace interaction, but also provide the only means for comprehensively validating increasingly sophisticated global numerical models. We can now observe the upper ionosphere, plasmasphere, ring current, cusps, and magnetosheath with, for example, optical, total electron content (TEC), extreme ultraviolet (EUV), far ultraviolet (FUV), energetic neutral atoms (ENA) and soft X-ray observations made by both ground-based arrays and spacecraft missions.

**The goals of this FST are to consolidate community efforts (1) to identify critical system-science questions that can be best addressed by global imagers and distributed arrays, now or in the near future, and (2) to determine how to maximize the system-science return by addressing the identified key system-science questions including the examples below.** This FST addresses SSA-1 (Geomagnetic Variability) and SSA-4 (TEC). This FST is particularly timely in light of the plans for the forthcoming GOLD, ICON, and MEDICI missions.

- To what extent can the motion of the magnetopause and cusp be used as indicators of magnetic flux transfer, and how does it affect the ring current, plasmasphere and aurora?
- What is the global evolution of ring current energy density ( $H^+$  and  $O^+$ ) and associated magnetic field structure of the inner magnetosphere, and how do those relate to global field-aligned current patterns?
- How do plasmaspheric and upper-ionosphere densities evolve during geomagnetic storms and what is their relationship to electric field and conductance distributions in the sub-auroral ionosphere?
- What is the causal flow of events between the solar wind, ring current, plasmasphere, upper ionosphere, and sub-auroral electric fields?
- How do auroral dynamics and the global ring current evolution relate to ion energization in the magnetosphere?

### **Goals and Measures of Success:**

- Quantitative assessment of how well the scientific questions can be addressed by global imaging and distributed arrays, and identification of knowledge gaps that can specifically be bridged by global observations. Comparative evaluation of validated algorithms that extract quantitative information of the source particle populations or boundaries (including uncertainties).
- Assessment of how current or new methodologies should be developed to maximize the science return from future global imaging missions or distributed array measurements.

- Community-wide engagement to disseminate scientific results and an increased accessibility to global observation analysis tools and products

### **Types of Investigations:**

- Investigations that employ simultaneous observations from global imaging or distributed arrays to explore the causal relationship(s) between magnetosheath, cusp, auroral oval, ring current, plasmasphere, and upper ionosphere phenomena.
- Implementation and validation of techniques that retrieve the 3D particle distributions and boundaries of the upper ionosphere, plasmasphere, ring current, magnetosheath, and cusps, including tomography, inversion, and forward modeling. This includes efforts making use of synthetic data to establish the feasibility and usability of imaging data where there is only limited real data, and benchmarking efforts.
- Use of global observations in global physics models to constrain physical mechanisms.
- Studies that enable new or significant improvement of existing empirical global models using global observations.
- Investigations that use global data from missions including GPS spacecraft, Cosmic-1 and -2, IMAGE, TWINS, IBEX, Polar, Chang'E, ROSAT, and XMM.

# Understanding Global-scale Solar Processes and their Implications for the Solar Interior

## Target Description:

The particulate and electromagnetic outputs of our star are modulated by the gross behavior of the Sun's magnetic field. That field, on timescales from seconds to millennia, shapes the interaction of our star with our home. Unfortunately, the processes that drive the genesis and much of the evolution of global-scale magnetic field are largely hidden from direct observation.

As a result, models of solar magnetic flux origins have attempted to explain the generation and evolution of the magnetic field using assumptions about the internal flow fields including temporally varying differential rotation, meridional flows, and zonal flows, as well as estimates of reconnection rates and diffusion times of the field. However, recent observational research has highlighted the presence of more complex meridional circulation patterns and significant differences in evolution of the higher latitudes that may play a major, but previously uninvestigated, role. The assimilation of time-variable, large-scale, internal solar dynamics into models of solar magnetic flux origins is essential for forecasting solar magnetism, activity, resulting geomagnetic effects and satellite drag across the relevant timescales and is therefore relevant to SSA-0, SSA-1, and SSA-2.

This FST should develop a consensus set of observational constraints for the latitudinal and temporal variation of meridional circulation, the solar rotation profile, etc., using state-of-the-art observation and data analysis techniques from historical and contemporary data archives. This FST will bring together observers to provide information on the internal flows, with solar interior modelers to provide the simulations, and data assimilation experts to construct a framework to intertwine observation and model.

**The overarching goal of this FST would be to produce a data-driven model for solar magnetic flux production to enable forecasting of active latitude and longitude regions on time scales ranging from years to decades.** Bringing together observers, analysts, modelers, and theorists to work together are a necessary prerequisite to development of forecast capability for solar activity across scales, in readiness for the ~2022-23 maximum of solar cycle 25 in direct support of Solar Orbiter and Solar Probe Plus mission science.

## Goals and Measures of Success:

- The project will advance our understanding of the time-variable and large-scale internal solar dynamics. Success can be measured by the degree to which the team improves the forecasting of solar inputs to heliospheric and terrestrial atmosphere models beyond rotational time scales.
- The team will develop a “consensus” set of observational constraints of surface and interior flows that extend the present reliance of the modeling community on sunspot archives, including hemispheric and broader latitudinal dependence.
- The team will demonstrate how to incorporate observations into models of the flows and magnetic dynamo activity of the solar interior. Measures of success are the prediction of the magnitude and timing of the next solar cycle maximum and the prediction of active latitudes during the next solar cycle.

- Validation of predictive tools will be addressed through hindcast comparisons with legacy observations.

### **Types of Investigations:**

- Observational studies to identify monthly to decadal timescale variations in internal flows, and numerical studies of how these affect internal dynamo action.
  - Novel data analysis techniques: Methods tailored to measure large-scale flows in the photosphere and solar interior 1) with high spatial resolution 2) that reach to high latitudes.
  - Use of feature-finding algorithms: Investigations which explore existing community resources (e.g., the Heliophysics Events Knowledgebase; HEK) and develop methodologies for identifying and tracking features in magnetograms and solar imaging in contemporary and legacy data to derive further information about global-scale flows.
  - Use of ancillary observations as additional constraints: Investigations which explore the relationships and differences between global-scale evolution observed in the low and high latitudes using data of the photosphere, chromosphere and corona in addition to archived measures of the solar wind and sun-as-a-star radiative properties.
- Observational studies of the spatial structure of internal and surface solar flows, and numerical studies of how these affect internal dynamo processes and active flux emergence latitudes.
  - Inversion techniques: Development of new helioseismic methods for pushing the range of validity in latitude and in depth (shallowness) of the various diagnostics, including the use of multiple line techniques with different sensitivities to the presence of magnetism.
  - Diagnostic intercomparisons and validation, with observational investigations including helioseismology (based on observations or numerical simulations), the nature of super-granulation, giant cells, etc.
- Studies to develop assimilative methods required to incorporate observed solar flows into flux evolution and dynamo models.
  - Theory and modeling of large-scale flows and generation of magnetic fields in the solar interior.
  - Data assimilation into predictive tools for near-real-time updating is encouraged. The investigations must emphasize how development enables emergence of predictive capabilities.

### **Focus on Enabling Predictability and Interaction with User Communities:**

The orbital-drag community is a prime user because of their reliance on information concerning the strength and timing of future solar cycles with radiative models of the same. In addition, NASA planning of human exploration relies heavily on understanding the solar cycle. NASA will facilitate coordination between the selected proposals and these user communities.



**Attachment:** LWS-TRT\_Connections\_to\_SWAP.xlsx

Item #	SWAP Action	Potential LWS TR&T Contributions	Potential SWORM Targeted Topics	Potential SWORM Targeted Strategic Capability (SC) Topics
1.1.1	(Induced Geo-E-fields): The Department of the Interior (DOI), the Department of Commerce (DOC), and the National Aeronautics and Space Administration (NASA), in coordination with the Department of Homeland Security (DHS), the Department of Energy (DOE), and the National Science Foundation (NSF), will: (1) assess the feasibility of establishing functional benchmarks using currently available storm data sets, existing models, and published literature; and (2) use the existing body of work to produce benchmarks for specific regions of the United States.	Shared goal with SSA-1 (Geomagnetic Forecasting Capability). Shared goal with LWS Institute on GICs (due for completion in 2017)	See Focused Science Topics (FSTs) for these SSAs in 2013, 2015 and 2016 LWT TR&T Steering Committee reports	
1.1.2	DOI, DOC, NASA, and NSF, in coordination with DHS and DOE, will assess the suitability of current data sets and methods to develop a more-refined (compared to Phase 1) set of benchmarks. The assessment will also identify gaps in methods and available data, project the cost of filling these gaps, and project the potential improvement to the benchmarks based on filling each gap.	See 1.1.1		
1.1.3	DOI, DOC, NASA, and NSF, in coordination with DHS and DOE, will improve on the induced geo-electric field benchmarks for the continental United States.	See 1.1.1		
1.2.1	(Ionizing Radiation): NASA and DOC, in coordination with NSF, the Department of Transportation (DOT), the Department of Defense (DOD), and the Federal Communications Commission (FCC), will: (1) assess the feasibility and utility of establishing functional benchmarks for ionizing radiation using the existing models and body of literature for this phenomenon; and (2) use the existing body of work to produce benchmarks.	Shared goal with SSA-3 (Solar Energetic Particles) and SSA-6 (Radiation Environment)	See FSTs for these SSAs in 2013, 2015 and 2016 LWT TR&T Steering Committee reports	
1.2.2	NASA and DOC, in coordination with NSF, DOT, DOD, and FCC, will assess the suitability of current data sets and methods to develop a more-refined (compared to Phase 1) set of benchmarks. The assessment will identify gaps in methods and available data, project the cost of filling the gaps, and project the improvement to the benchmarks based on filling each gap.	See 1.2.1		
1.2.3	NASA and DOC, in coordination with NSF, DOT, DOD, and FCC, will develop enhanced benchmarks.	See 1.2.1		
1.3.1	(Ionospheric disturbances): DOC and DOD, in coordination with NASA, DOI, NSF, and FCC, will: (1) assess the feasibility and utility of establishing functional benchmarks using the existing models and body of literature for this phenomenon; and (2) use the existing body of work to produce benchmarks.	Shared goal with SSA-4 (Total Electron Content) and SSA-5 (Scintillation)	See FSTs for these SSAs in 2013, 2015 and 2016 LWT TR&T Steering Committee reports	
1.3.2	DOC and DOD, in coordination with NASA, DOI, NSF, and FCC, will assess the suitability of current data sets and methods to develop a more-refined (compared to Phase 1) set of benchmarks. The assessment will identify gaps in methods and available data, project the cost of filling the gaps, and project the improvement to the benchmarks based on filling each gap.	See 1.3.1		
1.3.3	DOC and DOD, in coordination with NASA, DOI, NSF, and FCC, will develop enhanced benchmarks.	See 1.3.1		
1.4.1	(Solar Radio Bursts): DOC, DOD, and NASA, in coordination with DOI and FCC, will: (1) assess the feasibility and utility of establishing functional benchmarks using the existing models and body of literature for this phenomenon; and (2) use the existing body of work to produce benchmarks.	Shared goal with SSA-0 (Solar Outputs) and SSA-3 (Solar Energetic Particles)	See FSTs for these SSAs in 2013, 2015 and 2016 LWT TR&T Steering Committee reports	
1.4.2	DOC, DOD, and NASA, in coordination with DOI and FCC, will assess the suitability of current data sets and methods to develop a more-refined (compared to Phase 1) set of benchmarks. The assessment will identify gaps in methods and available data, project the cost of filling the gaps, and project the improvement to the benchmarks based on filling each gap.	See 1.4.1		

1.4.3	DOC, DOD, and NASA, in coordination with DOI and FCC, will develop enhanced benchmarks.	See 1.4.1		
1.5.1	(Upper Atm Expansion): DOC, DOD, NSF, and NASA, in coordination with DOI and FCC, will: (1) assess the feasibility and utility of establishing functional benchmarks using the existing models and body of literature for this phenomenon; and (2) use the existing body of work to produce benchmarks.	Shared goal with SSA-2 (Satellite Drag)	See FSTs for these SSAs in 2013, 2015 and 2016 LWT TR&T Steering Committee reports	
1.5.2	DOC, DOD, NSF, and NASA, in coordination with DOI and FCC, will assess the suitability of current data sets and methods to develop a more-refined (compared to Phase 1) set of benchmarks. The assessment will identify gaps in methods and available data, project the cost of filling the gaps, and project the improvement to the benchmarks based on filling each gap.	See 1.5.1		
1.5.3	DOC, DOD, NSF, and NASA, in coordination with DOI and FCC, will develop enhanced benchmarks.	See 1.5.1		
2.2.1	DHS, in coordination with NASA and DOC, will incorporate the latest data on the threats and vulnerabilities from extreme space weather into the next Strategic National Risk Assessment (SNRA).	Research from TR&T program available to provide info as required		
2.2.2	DHS, in coordination with DOC, DOD, and NASA, will ensure a consistent, joint message concerning the research, prediction, and preparedness for extreme space-weather events across the Federal Government.	Research from TR&T program available to provide info as required		
2.6.1	DHS, in coordination with DOC, DOD, NASA, and DOT, will develop training materials to familiarize scientific, national security, and emergency management professionals with the role and execution of emergency management protocols during the response to extreme space-weather events.	Research from TR&T program available to provide info as required		
4.2.3	DOC, in coordination with NASA, DOD, and DOT, will work with the commercial aviation industry, space operations and services, and international groups to define the requirements for real-time monitoring of the charged particle radiation environment to protect the health and safety of crew and passengers during space-weather events.	Shared goal with SSA-3 (SEP) and SSA-6 (Radiation): modeling of radiation into polar cap for aviation environment.	FST: Follow radiation from deep space through magnetosphere and atmosphere	SC: Forecasting SEPS and their response through magnetosphere and atmosphere
4.2.4	DOT, in coordination with DOC, the Department of State (DOS), NASA; and in collaboration with commercial aviation, space, and international stakeholders; will define the scope and requirements for a real-time reporting system that conveys situational awareness of the radiation environment to orbital, suborbital, and commercial aviation users during space-weather events.	see 4.2.3	see 4.2.3	see 4.2.3
4.2.5	DOC and DOT, in coordination with NASA, academia, the private sector, and international partners, will develop or improve models for the real-time assessment of radiation levels at commercial flight altitudes.	see 4.2.3	see 4.2.3	see 4.2.3
4.4.2	DHS and DOC, in coordination with NASA, NSF, private sector, academia, and other stakeholders, will develop a national capability for operational forecasting of space-weather impacts. The process will seek the development of new or improved forecasting models and the development of relevant tools and products that ensure the operational execution and dissemination of forecasts.	SSA 0-6 goals: Study physics required to develop forecasting of space weather	FSTs are focused on developing physics-based understanding required for improving models and developing forecasting capabilities	Development of SCs to advance, test and improve forecasting capabilities
5.3.1	DOC, NASA, and NSF will develop a strategy for: (1) the continuous operation of the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph (SOHO/LASCO) for as long as the satellite continues to deliver quality observations; and (2) prioritizing the reception of LASCO data in anticipation of extreme space-weather events.	SSA-0 (Solar Outputs): incorporation of remote solar observations for understanding the origin of extreme space weather events	FST: Scientific understanding needed for underpinnings of extreme space weather events	SC: improving forecasting models via use of comprehensive remote solar observations

5.3.10	DOC, NASA, NSF, DOD, and DOI will develop a plan to sustain the availability of facilities for the calibration of space-weather-observing assets to ensure that measurements are accurate and comparable through traceability to international standards.	SSA 0-6	Development of metrics and tests for improving space weather models and forecasting capabilities	SC: Test modeling forecasts in SSA 0-6
5.3.2	DOC, in coordination with NASA and DOD, will develop options to deploy an operational satellite mission to a position at least 1 million miles upstream on the sun-Earth line (e.g., the L1 Lagrangian point). The primary instrument on this mission will be a solar coronagraph to replace the SOHO/LASCO coronagraph capability. This mission will also provide solar wind measurements and other measurements essential to space-weather forecasting.	see 5.3.1	see 5.3.1	see 5.3.1
5.3.9	DOC, in coordination with NASA, DOD, and NSF, will produce a plan for deployment of new operational space-weather-observing assets to provide the baseline measurements outlined above. The plan will prioritize and define the required fidelity, cadence, and latency of ground-based and space-based measurements.	see 5.3.10	see 5.3.10	see 5.3.10
5.4.1	NASA and DOC will assess space-weather-observation platforms with deep-space orbital positions (including candidate propulsion technology), which allow for additional warning time of incoming space-weather events.	see 5.3.10	see 5.3.10	see 5.3.10
5.4.2	NASA, DOC, DOD, and NSF will support the development of novel sensor technologies and instrumentation to improve forecasting lead-time and accuracy.	see 5.3.10	see 5.3.10	see 5.3.10
5.4.3	NASA, DOC, DOD, and NSF will prioritize and identify needs for improved coverage, timeliness, data rate, and data quality for space-weather observations, and opportunities to address these needs through collaborations with academia, the private sector, and international community.	see 5.3.10	see 5.3.10	see 5.3.10
5.5.1	NSF and NASA, in collaboration with DOC and DOD, will lead an annual effort to prioritize and identify opportunities for research and development (R&D) to enhance the understanding of space weather and its sources. These activities will be coordinated with existing National-level and scientific studies. This effort will include modeling, developing, and testing models of the coupled sun-Earth system and quantifying the long- and short- term variability of space weather.	TR&T Steering Committee leads annual activity to prioritize science for achieving SSAs 0-6	FSTs will develop scientific understanding needed for tomorrow's forecasting capabilities	SC will develop, test and improve forecasting capabilities
5.5.2	NASA, NSF, and DOD will identify and support basic research opportunities that seek to advance understanding of solar processes and how the sun's activity connects to and drives changes on Earth and its near-space environment.	see 5.5.1	see 5.5.1	see 5.5.1
5.5.3	NASA, DOC, and DOD will identify and support research opportunities that seek to address targeted operational space-weather needs.	see 5.5.1	see 5.5.1	see 5.5.1
5.6.1	NASA and NSF, in collaboration with DOC and DOD, will develop a formal process to enhance coordination between research modeling centers and forecasting centers. This process will seek to identify roles and responsibilities in testing, verification, and validation for transitioning space-weather research models to space-weather-forecasting centers and for sustaining and improving models that transition into operations.	Modeling centers, such as the Community Coordinated Modeling Center (CCMC) will house and disseminate products developed within TR&T program	FSTs will develop understanding needed for developing SSA-targeted space weather models used by centers such as CCMC	SCs will develop, test and improve new SSA-targeted modeling capabilities that will be housed at centers such as CCMC, with the ultimate goal of transitioning to operations
5.6.2	DOC and DOD, in collaboration with NASA and NSF, will develop a plan (which may include a center) that will ensure the improvement, testing, and maintenance of operational forecasting models. This action will leverage existing capabilities in academia and the private sector and enable feedback from operations to research to improve operational space- weather forecasting.	TR&T Steering Committee will develop metrics for tracking progress in achieving SSAs. These metrics would apply equally well to SWAP goals, where they connect to SSAs.		

6.2.2	DOC and DOI, in coordination with NASA and NSF, will explore opportunities to leverage international partnerships to sustain baseline operational space-weather-observing capabilities.	TR&T program could, via FST's, foster use of international datasets		
6.2.3	DOC and NASA will collaborate with academia, the private sector, and the international community to explore the potential benefits and costs of space-weather missions in orbits complementary to the sustained missions at the L1 Lagrangian point, which may include missions at the L5 Lagrangian point. Such missions may improve monitoring of CME properties and trajectories relative to Earth.		FST: science exploration of L5 observation payoff for CME observations	
6.2.6	DOC and DOI, in coordination with NSF and NASA, will promote the improved exchange of data and information using the WMO Information System and other means, and organize international data comparison activities to promote the availability, intercalibration, and interoperability of space- and ground-based data.			
6.2.7	DOC and DOI, in coordination with NSF and NASA, will provide input to the WMO operational space-weather-observing requirements and Statement of Guidance and will report to relevant international organizations, including the COPUOS, the Coordination Group for Meteorological Satellites (CGMS), and the International Real-time Magnetic Observatory Network (INTERMAGNET), <sup>25</sup> on priorities for coordinated action.	LWS TR&T could contribute new observing technologies / capabilities to address SWAP actions. LWS TR&T research could give input on relevance / utility of various space weather measurements for predicting state of space environment.		
6.2.8	NASA will promote and support the continuation of space weather as a regular topic in the international efforts of the International Council for Science's Committee on Space Research (COSPAR) and within the International Living with a Star (ILWS) program.	LWS program shares common goals with ILWS		
6.3.3	DOC and NASA will continue efforts within CGMS to promote an ongoing agenda item on space-weather activities.	TR&T Steering Committee could encourage CGMS to make data available for future FST teams		