NASA Living With a Star (LWS) Targeted Research and Technology (TR&T) Steering Committee Report on Focus Science Topics, Tools, Strategic Capabilities and Updates to Strategic Science Areas

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Steering Committee Members:

Nathan Schwadron, UNH (Chair)
Brian Anderson, APL
John Leibacher, NSO
Jon Linker, Predictive Science
Mark Linton, NRL
Ramon Lopez, UT Arlington
Scott McIntosh, NCAR
Fabrizio Sassi, NRL
Karel Schrijver, LMATC
W. Kent Tobiska, Space Environment Technologies/SpaceWx
Daniel Weimer, Virginia Tech
Eftyhia Zesta, GSFC

Liaisons to TR&T SC:

Spiro Antiochos, GSFC
Masha Kuznetsova, GSFC
Slava Lukin, NSF
Kent Miller, AFOSR
Therese Moretto Jorgensen, NSF
Terry Onsager, NOAA
W. Dean Pesnell, GSFC
Ilia Roussev, NSF
David Sibeck, GSFC
Chris St. Cyr, GSFC
Adam Szabo, GSFC
Rodney Viereck, NOAA

LWS Program Ex Officio:

Madhulika Guhathakurta, NASA/HQ
Bob Leamon, NASA/HQ

1. Introduction

This report includes the results of deliberations by the LWS 2015 TR&T Steering Committee in formulation of focus science topics, strategic science areas and other topics for LWS TR&T. The committee met on three separate occasions: March 25-26, May 21-22, and July 15-17 in 2015. Note that LWS TR&T has formulated a set of long-term goals for *System Science,* termed Strategic Science Areas (SSAs), which are summarized in section 2. The committee has also decided to add one new SSA (SSA-0), detailed in the Appendix. The peculiar numbering for this SSA-0 was chosen because the long-term goal is considered as fundamental to the development of predictive understanding needed for future LWS advances. Section 3 details the focus science topics considered by the committee and section 4 details a strategic capability that may be an opportunity for future development.

2. Strategic Science Areas: Development of Physics-Based Understanding Leading to Predictability and Products Most Critical to User Communities

The LWS program has built a solid foundation on strategic capabilities, focused science topics (FSTs) and other investigations. We are now prioritizing opportunities to leverage suitable developments for the physics-based understanding leading to predictive developments in key areas of LWS science. FSTs, Strategic Capabilities (SCs) and the elements of LWS focus on separate long-term targeted areas of *System Science*, termed "Strategic Science Areas" (SSAs), requiring cross-disciplinary collaboration, for developing the understanding most critical to predictive development:

Physics-based Understanding to Enable Forecasting of:

SSA-0: Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth's atmosphere: The 2015 LWS SC formulated this new strategic science area (detailed in the Appendix) to develop physics-based understanding enabling forecast capabilities of the variability of solar magnetism, with a particular focus on better understanding of the processes that drive the formation, interaction, and emergence of magnetic flux systems in the solar interior on time scales from days to decades. Further, this SSA should advance understanding of the impacts of such flux systems for the space environment and the responses of Earth's atmosphere;

SSA-1, Geomagnetic Variability: The goal is to develop the physics-based understanding to enable 1 – 3 day (long lead-time) and 15 – 30 minute (short lead-time) forecasting, including predictability of pending severe geomagnetic disturbances;

SSA-2, Satellite Drag: The goal is to develop scientific capabilities that enable specification of the global neutral density in the thermosphere and its variations over time. This development will lead to the ability to predict the densities that satellites in low-Earth orbit will encounter with a lead-time of at least one hour as well as longer-term predictions out to at least three days and preferably to seven days or longer. There should be quantifiable levels of uncertainty that are specified for different data conditions and levels of redundancy in data/models;

SSA-3, Solar Energetic Particles: The goal is develop scientific understanding that enable probabilistic prediction of the spectral intensity of SEP events, and increased time periods for all-clear forecasts with higher confidence level;

SSA-4, Total Electron Content (TEC): The goal is to derive a model, or coupled set of models, that enable specification of the global ion density in the topside ionosphere and plasmasphere and its variations over time under varying geomagnetic conditions. The model or coupled models should develop the capability to predict the TEC observations globally, with a lead time of at least one hour (based on availability of real-time solar wind/IMF measurements), as well as longer-term predictions for up to three days based on solar wind forecasts;

SSA-5, Ionospheric Scintillation: The goal is to develop the scientific understanding necessary to predict scintillation occurrence utilizing limited sources of available data and ascertain how radio signals are degraded by ionospheric irregularities. Achieving this will require elucidation of the complete set of physical mechanisms responsible for producing ionospheric irregularities, the most important sources of free energy, and the causal chains that both generate and suppress irregularities leading to scintillations.

SSA-6, Radiation Environment: The goal is to develop a physics-based understanding of the atmospheric radiation environment from galactic cosmic rays (GCR) and solar energetic particle (SEP) sources, and the variabilities associated with cutoff rigidity, atmosphere density, and gamma-ray/X-ray inputs. Other success measures will include the development and application of new observational methods, both in situ and remote, that lead to new data sets for assimilation into models on global and regional scales, and new insights into the spatial/temporal scales of radiation storm variations that are affected by space weather.

3. Focused Science Topics

Measuring and Modeling the Solar Coronal Energy Buildup that Drives Space Weather

Target Description: Space weather driven by the Sun (SSA-1 to SSA-6) is ultimately due to the buildup and release of magnetic free energy in the Sun's corona. Consequently, understanding the processes by which free energy (or energy that can be readily converted) accumulates, measuring this buildup accurately, and modeling its evolution is critical for achieving the LWS goals. A key predictor of solar activity is free magnetic energy, which is defined as the difference between the actual magnetic energy in the corona and the energy of the current-free field with the same radial component at the photosphere. For a given radial component at the photosphere, the current-free field is the minimum energy state; therefore, in principle, the free energy is available to power flares, coronal mass ejections (CMEs), and other drivers of space weather. In numerical models, the free energy is a potential predictor of the onset of flaring and CME activity. With the advent of continuous high cadence full disk vector magnetograms from SDO/HMI, we now have the potential to measure quantitatively the observed injection of free magnetic energy into the corona by photospheric flux emergence and flows. In addition, high-resolution SDO/AIA observations of coronal structure are available for use in constraining the free energy determination. Furthermore, models are now available for performing self-consistent buildup of free energy via flux emergence/photospheric motions and for incorporating observational data into simulations.

This FST calls for a concerted observationally driven effort to quantify the level of free magnetic energy in coronal active regions and quiet-Sun prominence configurations. This effort will consist of observations of coronal energization, determined by both free energy proxies and by subsequent flaring/CME activity of the active complex; coupled with various data-driven and data-constrained models to model quantitatively this free energy injection and storage.

Goals and Measures of Success: The goal of this FST is to develop data analysis methods and models to measure accurately the free energy build up (Poynting flux/helicity flux injection) in active regions. Additional goals are to determine accurately how the energy evolves, where it collects, and disperses. Measures of success are validation of the developed methods and models with the energy release observed in CMEs/SEPs/flares/etc. Consequently, an auxiliary goal is to perform comprehensive accounting of the energy released in observed major solar eruptive events.

Types of Investigations:

- Studies that use observations of the photospheric velocity and magnetic fields, such as from SDO/HMI, to determine accurate, quantitative measures of energy injection into the coronal magnetic field.
- Studies that use coronal imaging data, such as from SDO/AIA, to derive constraints on free energy buildup and evolution.

- Studies that use various data sets and novel data assimilation methods for determining accurate constraints on free energy buildup and evolution.
- Studies that use theoretical models to determine how the free-energy level evolves in the corona, and the observational signatures of these processes.
- Numerical modeling of free-energy injection and evolution using the observations for input and for validation.
- Validation of free-energy levels in the corona, such as by studies that measure the energy release in events such as flares/CMEs/SEPs.

Interactions with User Communities: NASA will facilitate interaction between selected teams and user communities. FST proposals should identify how research elements enable predictive developments that would be significant to specific user communities.

Global Electrodynamics of the Ionosphere

Target Description: The large-scale electrodynamics of Earth's ionosphere reflects the state of magnetosphere–ionosphere convection, energy transport between the magnetosphere and ionosphere, and plays a key role in the dynamics of the ionosphere and thermosphere. This includes transport and heating of ionospheric plasma and the neutral atmosphere. At high latitudes the electrodynamics reflect magnetospheric convection and energy dissipation both via Joule heating and mechanical acceleration of the neutral gas. At middle and low latitudes the electric field is largely generated by the thermospheric winds although during storm times the high-latitude dynamics can substantially impact the low- to mid-latitude ionosphere through penetration electric fields and storm- time dynamo winds. Ionospheric electrodynamics determine the energy dissipation that drives thermospheric upwelling, reflects the convection driver for plasmaspheric plumes and TEC evolution, and governs where intense ionospheric electric fields occur that drive a range of ionospheric irregularities causing scintillation. Deriving ionospheric electrodynamics applicable for storm times is therefore of particular importance to: LWS SSA-2 Physics-based Satellite Drag Forecasting Capability; SSA-4 Physics-based TEC Forecasting Capability; and SSA-5 Physics-based Scintillation Forecasting Capability.

Most existing theories and models of the global electric field in the ionosphere focus on regional scales (e.g., limited latitudinal ranges), assume equipotential field lines, and/or impose ad-hoc or statistical boundary conditions that do not apply generally and in particular not to storm conditions. Quantifying dissipation and neutral wind dynamics, distinguishing between heating and mechanical acceleration, and understanding the relationships of electrodynamics to particle precipitation require concurrent knowledge of ionospheric conductivities. Measurement of the global electric field, field aligned currents, and ground magnetometer equivalent ionospheric currents can be used to solve ionospheric electrodynamics to infer the effective conductivities. However, in practice, differences in spatial and temporal coverage, and sampling cadence require use of assimilative approaches including as much information as possible for the conductivities and electrodynamics in under-sampled regions. In addition, the role of inter-hemispheric connectivity is often overlooked despite evidence of conjugate effects at sub-auroral latitudes.

To advance SSA-2, 3, and 5, it is critical to quantitatively characterize storm-time ionospheric electrodynamics observationally and validate existing empirical and physics-based models against the most complete suite of observations possible. Now is an opportune time to focus attention on this topic and overcome the deficiencies noted above given recent advances in modern computer technology and computational algorithms, and contemporaneous observations from space- and ground-based resources including C/NOFS, Swarm, AMPERE, mid-latitude and polar HF SuperDARN radars, new incoherent scatter radars, integrated ground magnetometer data via SuperMAG, and DMSP SSUSI. This Focused Science Topic targets the determination of storm-time ionospheric electrodynamics from observations as fully as possible using these recent data sets and quantitatively testing existing empirical and physics-based models, and deriving advances in modeling capabilities to improve quantitative predictive capability.

The FST should motivate future research into the roles of neutral winds and auroral structuring for ionospheric electrodynamics. In particular, characterizing the role of neutral winds in modifying energy transport and dissipation, and the contributions of smaller scale field and precipitation structures (below ≈10s of km) in altering energy dissipation and creating density irregularities may be significant.

Goals and Measures of Success: The goals of this FST are to provide an improved understanding that would enable a predictive capability of storm-time ionospheric electrodynamics. Specifically: (1) assess storm-time ionospheric electrodynamics from observations including the ionospheric conductivity, currents, and electric fields; (2) quantify the validity of existing empirical and physics-based models of ionospheric electrodynamics; (3) identify key areas of discrepancy and assess techniques, including potentially data-assimilation, to incorporate available data into ionospheric/thermospheric models and to infer external forcing where not well measured.

Types of Investigations: This FST intends to bring together modelers and observers who can make progress toward deriving storm-time ionospheric electrodynamics, validating existing models, and identifying and/or substantially improving existing modeling systems. Efforts are solicited in several areas: a) derivation of ionospheric electrodynamics from the broadest available suite of observations; b) empirical and/or first-principle theory and modeling of the global electrodynamics of the ionosphere for comparison against the observationally constrained electrodynamics; c) further development/assimilation of global data sets into the models to advance the capability to predict storm-time ionospheric electrodynamics.

Data and tools to be used: FST proposals would make good use of the following types of data and tools:

- Global magnetospheric, ionospheric, and thermospheric models;
- Solar wind and solar irradiance measurements as well as solar indices and geomagnetic indices;
- Spacecraft data and data products for example from C/NOFS, CHAMP, Swarm, AMPERE, DMSP, and other sources;
- Ground magnetometer and radar data including HF and ISR systems;
- Assimilation algorithms to derive observations-based global determinations of ionospheric electrodynamics incorporation derivation of conductances.

Interactions with User Communities: NASA will facilitate interaction between selected teams and user communities. FST proposals should identify how research elements enable predictive developments that would be significant to specific user communities.

Innovative use of Data in Coronal/Solar Wind models

Target Description: The Sun's corona and solar wind play a critical role in space weather. Understanding of the global state of the corona and inner heliosphere thus underlies nearly all of the LWS SSAs, and especially SSA-1 (Physics-based Geomagnetic Forecasting Capability), SSA-3 (Physics-based Solar Energetic Particle Forecasting Capability), and SSA-4 (Physics-based TEC Forecasting Capability). Moreover, the topic is timely, given the upcoming Solar Orbiter and Solar Probe Plus Missions.

Currently, models of the solar corona and solar wind rely primarily on maps of the photospheric magnetic field, available from a number of ground-based and space-based observatories to generate steady state solutions. Remote observations, such as EUV, white light, as well as *in situ* measurements, are used to validate and test model solutions. This topic focuses on the innovative use of heliophysics data to address the time-dependent state of the inner heliosphere. Methods such as "data assimilation", and "ensemble modeling," which are used in the meteorological community, can be highly beneficial in this context. However, we recognize that the nature and sparseness of heliophysics data means that these techniques may not be directly translatable to the solar/heliospheric environment, but must be adapted using novel techniques. The innovative use of sequences of magnetograms and/or magnetic maps is also encouraged, as are the possible use of future measurements. For example, planning is needed for the use of multi-viewpoint magnetograms, as will be possible with Solar Orbiter, as well as the use of future Solar Probe Plus in situ measurements.

Goals and Measures of Success: The goal of this focus team will be to develop quantitative methods for incorporating heliophysics data into models, such that the techniques can eventually be used to produce a (near) real-time description of the solar corona and inner heliosphere, consistent with available data and suitable for modeling other processes (such as the propagation of CMEs).

Possible types of investigations: Investigations could include, but are not limited to:

- Studies that utilize EUV, white light, radio, IPS, and other space-based or ground-based data (such as coronal magnetometry) to modify/improve/correct model estimates of relevant parameters, such as values at L1.
- Studies that innovatively use magnetograms/magnetic maps to drive models
- Studies that develop mathematical techniques for incorporating data into coronal/solar wind models (e.g., assimilation or data driving, etc.)
- Studies that develop ensemble modeling techniques for improved predictions/quantification of uncertainty
- Studies that derive coronal/solar wind state quantities (i.e., density, temperature, velocity) such that they could be used to drive/modify/improve/correct coronal/solar wind models.

It is sufficient to demonstrate the above concepts in simple models; the use of a sophisticated model may be desirable but is not required. It is anticipated that selected PIs will collaborate and identify specific time periods to model, for comparison between and validation of the different approaches. As such, proposals should include sufficient travel funds in their proposed budgets to cover one meeting per year to be held in the US for this purpose.

Interactions with User Communities: To facilitate useful validation activities and communication of the results to user communities, the LWS Program Officer will contact relevant modeling/operational centers to identify liaisons for the project. Liaison(s) will be encouraged to participate in the annual meetings.

Large-Scale Sub-Surface Solar Flows

Target Description: The physics giving rise to both geomagnetic storms and sustained satellite drag originates in the spatial and temporal distribution of the solar photospheric magnetic field, which, in turn, arises from the motions of the plasma inside the Sun. Models of solar magnetic flux origins attempt 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. The assimilation of time-variable, large-scale, internal solar dynamics into models of solar magnetic flux origins is essential for forecasting geomagnetic effects and satellite drag across the relevant timescales. The topic therefore is relevant to SSA-0, SSA-1, and SSA-2.

This FST should determine the variation of meridional circulation and differential rotation using state-of-the-art data analysis techniques. The variation of the solar internal rotation, zonal and meridional flows are closely associated with the solar activity cycle. The changes in rotation seen so far for Solar Cycle 24 are significantly different from those measured during Solar Cycle 23, as are other activity cycle manifestations, and the sources need to be understood.

State-of-the-art global and local helioseismology and image analysis techniques give us exquisite monitoring tools for these flows, and observations from the Solar Dynamics Observatory (SDO) give us the data needed to continue this monitoring. From a helioseismic perspective, SDO/HMI provides data and opportunity to improve on past techniques used for MDI (and ongoing with GONG). HMI provides high resolution images that permit us to access near-surface flows that are traceable to higher solar latitudes with high spatial degree modes. Advances in numerical modeling and computational power enable the relaxation of assumptions and simplifications made previously that have hampered progress in this area.

Models of solar magnetic flux origins are now being improved by incorporating estimates of the internal flows instead of *ad-hoc* assumptions, but they are not yet reliable enough for forecasting the characteristics of the activity cycle let alone evolution on timescales of days to months needed for useful forecasts. One path towards the goal of accurate and timely forecasts of active region locations, sizes and polarity is to routinely assimilate such data into models as is done in forecasting terrestrial weather.

Progress has been made along these lines in solar physics for the surface magnetic field using systems such as the AFRL ADAPT model, or the Lockheed approach, and there have been two similar efforts for dynamo models, but this area would benefit from a focused topic to bring together helioseismologists to provide the internal flows, dynamo modelers to provide the simulations, and data assimilation experts to construct the system framework. Investigations would be to evaluate the effect of parameter choices in each step on the accuracy of the forecast.

The overall goal would be to produce a data-driven model for solar magnetic flux production to enable forecasting of active latitude regions and on time scales ranging from years to decades. Success would be measured by skill scores using historical observations and then attempting actual forecasts. The deliverable would be either a working forecast tool, or an evaluation of the highest-priority research areas for further progress.

The topic is timely because of the high-spatial resolution observations from SDO/HMI and the emergence of new surface tracers of meridional circulation. Bringing together observers, analysts, modelers, and theorists involved in inversion to work together are a necessary prerequisite to development of a predictive capability

Types of Solicited Investigations

- **Novel Data analysis techniques to replace or augment existing methods** that may be 20+ years old, or are not tailored for measuring flows with 1) high-spatial resolution reaching to high latitudes and the poles and 2) very close to the surface.
- **Diagnostic intercomparisons, and validation**: data types include helioseismology (based on observations or numerical simulations), super-granulation and giant cells, bright points, etc…
- **Inversion techniques:** develop new methods for pushing the range of validity in latitude and in depth (shallowness) of the various diagnostics
- **Theory and modeling** of large-scale flows and of magnetic-flux emergence and transport
- **Data assimilation** into predictive tools for near-real-time updating is encouraged. The investigations must emphasize how development enables emergence of predictive capabilities.

Goals and Measures of Success:

- Validation of predictive tools will be addressed through comparison with legacy observations and more recent data. Metrics will be developed to evaluate the accuracy of predictive tools
- The project will advance our understanding of the time-variable and large-scale internal solar dynamics for forecasting short- and long-term changes in the heliosphere, geomagnetic effects, and satellite drag. Success can be measured by the degree to which the team improves the forecasting of solar inputs to heliospheric and terrestrial atmosphere models on rotational and annual scales.
- The team will demonstrate how to incorporate observations into surface-magnetic-flux-transport models, and how to create predictions of flux-emergence, solar irradiance, and solar-cycle-strength. Hence, the team will demonstrate how observations can be used to improve our quantitative description of the complete chain from the solar dynamo to geo-effective impacts. A measure of success is the prediction of the magnitude and timing of the next solar cycle maximum.

Interactions 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. In addition, NASA planning of human exploration relies heavily on understanding the solar cycle. NASA will facilitate coordination between the selected and these user communities.

Improving Geomagnetic Storm-Time Neutral Densities for Satellite Drag

Target description: The largest uncertainty in determining orbits for satellites operating in low Earth orbit (LEO) is the atmospheric drag. By far the largest contributor to satellite drag is dynamic changes of the thermospheric density. Drag is difficult to model because of the complexity of neutral atmosphere variations driven by the Sun's irradiance and charged particle energies coupled with the mesosphere–ionosphere–thermosphere (M-I-T) system; there is a contributing factor of lower atmosphere energy that propagates from below. Currently, atmospheric neutral density models routinely used in orbit determination applications are empirical and, although they have been significantly improved in recent years, more accuracy is needed during storms. Empirical models are based on historical observations to which parametric equations have been fit, representing the known variations of the upper atmosphere with local time, latitude, season, solar, and geomagnetic activity. First-principle (or physics-based) models can provide information about the atmospheric density conditions. Taking into account the interactions between upper atmosphere winds, composition and densities, first-principle models should be able to provide a more realistic representation of neutral density in the upper atmosphere. This is particularly true if the magnitude, spatial distribution, and temporal evolution of the solar and magnetospheric sources can be defined with sufficient accuracy, especially in long-duration geomagnetic storm events. The focus of this topic is to improve the understanding of neutral density variations, particularly during geomagnetic storm-time conditions, for satellite drag applications. The topic therefore addresses SSA-2: Physics-based satellite drag forecasting capability.

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), that result from geomagnetic storm-time conditions. Comparisons of both empirical and physics-based models of the density during storms to existing in-situ and remote-sensed satellite density data is critical to evaluating the success of these models. Proposals should suggest metrics that elucidate reductions in density variability uncertainty.

Types of Investigations: This solicitation seeks investigations that focus on the improvement of empirical and physics-based models. Areas needing improvement will be found through comparison of modeled neutral density with existing observations during geomagnetic storm periods; this will help improve, verify and validate modeled density variations. How models vary with different solar and magnetospheric inputs is a desired research area, including the use of spectral irradiances and spectral proxies or indices beyond F10.7 and geomagnetic indices beyond Ap. It is anticipated that model–data comparisons will lead toward nearer-term ensemble modeling that may help quantify neutral density uncertainties.

Interactions 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 utilize methods for reducing geomagnetic storm-time upper atmosphere densities in satellite drag applications.

Additional Note: The LWS SC recognizes that mechanisms should be explored to broaden the use and availability of density databases.

Advancing the Characterization of Earth's Atmospheric Radiation Environment

Target Description: The Radiation Environment Strategic Science Area (SSA-6) outlines broad needs for advancing the characterization of the science of the radiation environment. The radiation environment between the troposphere and space is variable and can change rapidly from galactic cosmic ray (GCR) and solar energetic particle (SEP) influx, i.e., heavy ions, neutrons, protons, beta particles, gamma-rays and X-rays. In addition, and of particular relevance to human tissue as well as avionics radiation dose and dose rate risks, secondary and tertiary particles from these sources can vary with changes of target atoms and molecules, such as in the tropospheric air mass or artificial shielding properties. The GCR background is typically variable on the timescale of days with a long-term trend that changes slowly and is modulated by the solar interplanetary magnetic field (IMF) varying with the approximate 11-year solar cycle. The SEP environment, however, can be highly time variable, with impulsive, order of magnitude changes associated with solar eruptive events occurring in a matter of seconds to minutes. Together, the GCRs and SEPs couple with the Earth's Magnetosphere–Ionosphere–Thermosphere (M-I-T) system and create the "weather" of the ionizing radiation environment.

Recent observations and modeling developments have permitted substantial progress in understanding the drivers to and responses in the radiation environment. For example: modeled global radiation climatology specifications from both the Civil Aerospace Medical Institute (CAMI) and the Nowcast of Atmospheric Ionizing Radiation System (NAIRAS) exist; the *Earth-Moon-Mars Radiation Environment Module* (EMMREM) provides estimates of the radiation environment from deep space to the ground. Measurement capabilities are rapidly expanding with the Automated Radiation Measurements for Aviation Safety (ARMAS) system that has demonstrated real-time dose rate measurements at commercial aviation altitudes. The energetic particle measurements throughout Earth's radiation belts on the NASA LWS Van Allen Probes mission, the boundary condition specification of the radiation environment measured by the NASA LRO/CRaTER instrument at the Moon, the NASA ACE mission at L1, the PAMELA observations of inner radiation belt protons within the thermosphere, and even the upcoming Rad-X high-altitude balloon flights all successfully show the maturity that radiation environment measurements have developed over the past several years. However, the variability and prediction potential of the coupled systems describing this radiation environment are not yet well quantified and this remains a long-term community research goal. First principles and empirically based models, combined with new data streams, are needed to achieve substantial progress toward future predictability. In the near-term, there is great value in comparing existing models and observational data sets for validation, leading to an ability to conduct ensemble modeling so as to characterize uncertainty in the radiation environment.

Goals and Measures of Success: The primary goal of this FST is to promote existing data–model comparisons for the global radiation environment, ranging from the lower atmosphere to space during quiet (GCR background at both solar minimum and solar maximum) and active (SEP event) conditions. An additional goal is to promote the continued innovative expansion as well as development of calibrated data sources that can help understand the dynamic variation of this radiation environment in near real-time. A critical measure of success for investigations through this FST will be the demonstrated comparison of the temporal, spatial, and magnitude variability in the radiation environment, from tropospheric altitudes to deep space, using observations and existing models, reported with appropriate metrics of uncertainty.

Types of Investigations: In support of SSA-6 (Physics-based Radiation Environment Forecasting Capability), this FST intends to bring together modelers and observers who can make progress toward validating existing modeling systems. While future predictive capability is needed, this solicitation does not encourage the development of fundamentally new models at this time. Instead, the user communities, including government agencies, international partners, and commercial airlines, have expressed strong interest in understanding the accuracy and uncertainty of existing models and data. This FST encourages proposers to make results of these comparisons available to users. Individual proposals may show how they support the FST with a systematic approach for comparing and validating modeling approaches that lead to model/observational validations. Investigations that can also validate calibrated dose and dose rate measurements for helping with these comparisons are especially solicited. Proposals that improve our understanding of radiation variability based on parameters such as cutoff rigidity, atmospheric density, and modulation potential are particularly useful for improving future modeling and defining the sources of uncertainty.

Interactions with User Communities: NASA will facilitate interaction between selected teams and user communities. FST proposals should identify how research elements enable predictive developments that would be significant to specific user communities.

Evaluation and Improvement of Magnetospheric Model Performance over Long-duration Runs

Target Description: Global models of the magnetosphere–ionosphere system have developed substantially over the past decades and are now mature enough to enable quantitative scientific investigations of magnetospheric processes and for operational, predictive services. Currently, magnetosphere models use solar and solar wind inputs to predict the global conditions throughout the magnetosphere, ionosphere, and on the surface of Earth. However, there have been very few long-duration (a continuous run of one or more months of duration) evaluations of the ability of magnetospheric models to reproduce a variety metrics of potential interest to the LWS program (e.g., d*B*/d*t* on the ground, magnetopause position, substorm occurrence, plasma sheet density and temperature, Birkeland current distribution and intensity, MHD wave spectrum and power spectral density, etc.). Quantification of these abilities can contribute significantly to identifying priorities for improving the models and to the transition of models to operations as well as the ability of the models to run in an operational mode, responding to a broad range of solar wind input. This activity can support SSA1 (Physics-based Geomagnetic Forecasting Capability), SSA2 (Physics-based Satellite Drag Forecasting Capability), SSA-4 (Physics-based TEC Forecasting Capability), SSA-5 (Physics-based Scintillation Forecasting Capability), or SSA-6 (Physics-based Radiation Environment Forecasting Capability), depending on the specific metrics for which prediction efficiencies are determined using archival data. For example, quantifying the ability of a model or models to determine the average d*B*/d*t* on the ground directly contributes to SSA1, while the accurate prediction of Birkeland current distribution and intensity is important for SSA2.

Furthermore, although numerous measurements are routinely being made within the magnetosphere and on the ground, these data are not yet used to improve the models during their execution. Using data assimilation for magnetosphere–ionosphere models has unique challenges in that the data are sparse and the system is strongly driven. Conventional data assimilation techniques used in meteorology, for example, are unlikely to be effective. Consequently, new techniques need to be developed to enable the use of available data for improving magnetosphere modeling. For example, rather then using data to nudge the model values at individual observation locations, the data could potentially be used to identify how to adjust parameters of the model (such as the ionospheric conductivity), or include effects (such as ionospheric ion outflow) that improve the prediction efficiency of the model relative to the chosen metric or metrics. Quantification of the improvements in model prediction efficiency would point to areas where a better understanding of the basic science can result in even better model prediction efficiency when the model is run for long durations, and thus responding to a variable solar wind input.

Goals and Measures of Success: This FST will result in evaluations of long-term prediction efficiency of magnetospheric models. This FST will also investigate data-assimilation capabilities to utilize available ground-based and space-based data to improve the specification and forecasting of global, physics-based magnetosphere models. This research will use the existing data and models to quantify the sensitivity of the model predictions to changes in internal model parameters, and it will develop methods to adjust the model to improve the agreement between the model and the data.

Possible types of investigations:

- Studies of the long-duration runs of magnetospheric models and the evaluation of model prediction efficiency for long-duration runs of metrics of interest (skills scores, probabilistic forecast scores, comparisons to empirical models, identification of types of solar wind input that result in good/bad predictions, etc.) relevant to LWS program goals
- Development of approaches to modify model parameters based on model–data comparisons (limiting factor or critical path analysis, such as the effect of ionospheric outflow or conductivity models) and the identification of a path forward for model development.
- Development or adaptation of data assimilation techniques and the evaluation of the effect of data assimilation on the prediction efficiency of long-duration runs.
- Sensitivity studies of the variation in the prediction efficiency of model outputs for long-duration runs as a result of varying model parameters, or including a variety of data assimilation techniques.

Focus on Predictability and Interactions with User Communities: It is expected that the supported investigations will quantify the ability of models to predict quantities of specific interest to users, as well as to improve predictive abilities and identify area of required future research. NASA will facilitate interaction between the selected team and user communities.

4. Strategic Capabilities

Solar Magnetic Inputs to Coronal and Heliospheric Models

Target Description: A quantitative description, and ultimately prediction, of the global solar corona and inner heliosphere is essential to nearly all of the Strategic Science Areas (SSAs), but is especially important for SSA-1 (Physics-based Geomagnetic Forecasting Capability), SSA-3 (Physics-based Solar Energetic Particle Forecasting Capability) and SSA-4 (Physics-based TEC Forecasting Capability). A crucial input to models of the solar wind, whether they are empirical or physics-based, is the magnetic field at the solar surface. Models frequently use synoptic magnetic maps derived from photospheric magnetograms that are available from a number of ground- and space-based observatories, including, but not limited to: GONG, SOLIS, MDI, and HMI. Current global models of the solar corona and inner heliosphere are driven by such observations, but are severely hampered by their deficiencies. In particular, the "synoptic" (really should be called "diachronic") maps, which are built up from individual full-disk magnetograms taken over the course of a solar rotation, 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 are what a global model requires. Second, these maps often differ substantially from one observatory to the next. Third, the fields in the polar regions are poorly 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. 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 five years worth of data from the HMI instrument onboard SDO and the launch of Solar Probe Plus (SPP) and Solar Orbiter in three years, a rigorous approach to the use of magnetograms and magnetic maps in quantitative models of the corona and solar wind is both timely and necessary. Additionally, the widespread availability of full-disk vector magnetograms at high temporal cadence may lead to new insights into the best use of these data.

Desired Products: The goal is to obtain the best quantitative maps of the radial magnetic field at the photosphere for the purposes of predicting coronal and solar wind parameters (e.g. solar wind speed, IMF polarity, coronal hole boundaries, open magnetic flux, plasma parameters, etc.).
Expected features include:

- Inter-calibration and comparison of line-of-sight magnetograms from NASA missions (e.g., SOHO/MDI and SDO/HMI) with measurements from ground-based observatories (e.g. NSO/SOLIS and NSO/GONG) to obtain a quantitative understanding of the differences between estimate(s) of the Sun's magnetic field

- Quantitative characterization and assessment of the accuracy of different techniques used to estimate and incorporate the Sun's polar magnetic field in maps.
- Combinations of vector magnetograph data (when available/feasible) with line-of-sight data to improve the estimate of the Sun's global radial magnetic field
- Sets of reformulated/recalibrated full-Sun synchronic maps made publicly available at a cadence commensurate with the capabilities of different observatories, suitable for incorporation into solar models as boundary conditions.
- Delivery of codes/models for taking observatory data, such as individual magnetograms, and producing the above maps. This could include, but does not require flux transport algorithms/models.
- Quantitative assessment and comparison of the different magnetic field maps to produce more accurate predictions of coronal and solar wind model parameters. This should, at a minimum, use source-surface models but may include more sophisticated models.

Possible (not required) features may include:

- Incorporation of estimates of the Sun's field not visible from Earth, such as helioseismic far-side images
- Quantitative description of the evolution of the Sun's surface magnetic field via flux transport models

It is anticipated that initial versions of the expected products will be developed and delivered in the first 3 years of the project. The final two years of the project will engage modeling groups/teams to use the products in a planned validation exercise – including how different models perform with the same map, and how a single model performs with different maps. This exercise will presumably lead to further inter-comparison and improvements in the data products/codes.

Focus on Enabling Predictability and Interactions with User Communities: So that the user/operational communities can directly benefit from Strategic Capability products, the LWS Program Officer will contact relevant modeling/operational centers to identify liaisons for the project. It is anticipated that this interaction will help advise on metrics for validation exercises.

Appendix

SSA-0 Physics-based Understanding to Enable Forecasting of Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and inputs to Earth's atmosphere

The goal is a physics-based understanding that will enable *forecast capabilities* for the variability of solar magnetism, with a particular focus on a better understanding of the processes that drive the formation, interaction, and emergence of magnetic flux systems within the solar interior and their implications for the space environment and responses of Earth's atmosphere. Success measures will include the development and application of observationally constrained modeling efforts across the LWS discipline that lead to insights into, and therefore improved forecast capability for, solar-forced electromagnetic, energetic particle, and plasma drivers of the space environment and the Earth's atmospheric inputs across temporal scales from years to centuries.

Basic Science Components: Characterizing the properties of the solar convective interior remains a significant challenge for our community, in order to understand the response of the rest of the space environment and Earth's atmosphere. The properties of the solar interior are required as constraints for investigations of the solar magnetism that lie at the heart of our interaction with the Sun. Largely masked from direct observation, the flows and feedbacks between the magnetic field and large-scale flows of the solar interior drive the persistent modulation of our star's electromagnetic, energetic particle, and plasma and includes eruptive output that in turn drives variability throughout the space environment and the upper terrestrial atmosphere.

The "unusual" temporal extension, and depth, of the 2009 solar minimum in addition to the episodic, but relatively subdued output of Solar Cycle 24, have underlined deficiencies in established theories. These conceptual roadblocks have placed a premium on observational investigations of solar interior structure and understanding large-scale evolutionary patterns visible in the historical data such as the "Torsional Oscillation" and even the "given" patterns of differential rotation, as well as meridional circulation.

At a time when solar activity may be in a significant, but gradual long-term decline, it is imperative for our community to develop stronger feedbacks between observation, remote sensing techniques, and modeling efforts of the solar interior to place stronger constraints on the latter. Enabling development of robust data-assimilation methodologies for forecasting the evolution of the system is needed. Such, well-constrained models can then be used to inform modeling and forecast activities of global solar activity across the international community.

We are seeking studies that will provide a science-based understanding and forecast capability for the variability of solar magnetism. We are especially encouraging studies that will place a particular focus on a better understanding of the physical processes that drive the formation, interaction, and emergence of magnetic flux systems in the convective solar interior across the timescales relevant to the variability of space climate.

Success measures will include the development and application of observationally constrained modeling efforts across the LWS discipline that lead to insights into, and therefore improved forecast capability for, solar drivers of the heliospheric system.

Models

- Observationally testable models of large-scale flows in the solar interior that relate to, and push advances in, observational techniques.
- Models of helioseismic signatures in and around the complex interfaces likely in the convective interior.
- Models of magnetic flux production in a rotating convective plasma with observationally testable outputs.
- Models of magnetic flux system interaction including the formation of complex active regions.
- Models of instabilities at the radiative–convective interface, tachocline, their detectability and their potential impacts on magnetic flux emergence and observational tests.

Observations: Interpretation of available datasets from the Solar Dynamics Observatory (SDO), Solar-Terrestrial Relations Observatory (STEREO), Hinode, Global Oscillation Network Group (GONG), Synoptic Optical Long-term Investigations of the Sun (SOLIS), and other space- and ground-based assets including long-term proxies of solar variability (e.g., Be^{10}, and other proxies).

Products

- Outputs capable of reproducing the large scale flow patterns of solar activity and their variability over wide-ranging timescales (up to centuries).
- Models of the decadal, annual and monthly solar magnetic activity to be used as drivers for electromagnetic, energetic particle, plasma and eruptive models of the solar system environment.
- Records and proxies of radiative and energetic particle inputs into the terrestrial system.

Potential User Base: NASA, DHS, DoD, DoE, FEMA, IPCC.

Metrics & Assessment

- All statistical analyses need to also address the uncertainty in the estimates of magnetic variability and flow characteristics.
- Capability to estimate onset and magnitude of global flux emergence events: start time, end time and maximum amplitude of the event.

Types of Investigation

- Consolidation and conservation of historical synoptic observational records.
- Development of methods to discriminate between the presence of subsurface magnetic fields and thermal structures in the convective interior;
- Determination of the cellular, or multi-cellular, structure of the plasma flow fields at all depths and latitudes at and below the visible surface of the Sun;
- Analyses revealing how the evolution of the flow field and magnetic environment of the solar poles can affect the dynamo and the solar activity cycle;
- Analysis across the spectrum of ground- and space-based platforms to exploit ancillary observations of the corona, solar wind, and heliospheric environment and help constrain the global evolution of the magnetized system;
- Development of methods to constrain and inform forecast models of solar activity on year to multi-decadal scales.
- Development of accurate historical records including proxies such as Be^{10} for solar activity

Implementation Specifics: The groups that will carry out the investigations will have experience on space-based solar physics data sets, analyzed (possibly jointly) with ground-based data, and modeling of key phenomena in the solar interior. As the primary goal of the studies is enabling improved predictive capability of magnetic variability, both empirical and first-principles modeling of key physical phenomena are appropriate approaches. The types of appropriate investigations (see also above "Types of Investigations") include theoretical modeling analyses of key physical processes, data analyses and comprehensive statistical analyses will improve our capability to predict the timescales and range of variability in solar activity across the timescales relevant to space weather and space climate investigations.