# NASA Living with a Star (LWS) Targeted Research and Technology (TR&T) Steering Committee (SC) Report, 2010-2011

*Date of Report*: June 21, 2011

*Members of the SC*:

Amitava Bhattacharjee, UNH, *Chair*
Pontus Brandt, JHU/APL
Edward DeLuca, SAO
Philip Erickson, MIT Haystack Observatory
Peter Foukal, Heliophysics, Inc.
Hugh Hudson, UC-Berkeley
Delores Knipp, CU
Yuan-Kuen Ko, NRL
Gang Li, UAH
Alexei Pevtsov, NSO
Peter Pilewskie, LASP
Peter Schuck, NASA/GSFC
Stan Solomon, NCAR
Bruce Tsurutani, JPL
Michael Wiltberger, NCAR

*Liaison to the SC*:

Cassandra Fesen, USAF AFMC AFOSR/RSE
Michael Hesse, NASA GSFC
Farzad Kamlabadi, NSF
Jeffrey Newmark, NASA HQ
Terry Onsager, NOAA/SWPC
Dean Pesnell, NASA GSFC
David Sibeck, NASA GSFC
Adam Szabo, NASA GSFC
Chris St. Cyr, NASA GSFC

*Ex Officio Members:*

Madhulika Guhathakurta, LWS Lead Program Scientist, NASA HQ
Charles Goodrich, LWS Discipline Scientist, NASA HQ
Robert Leamon, LWS Discipline Scientist, NASA HQ

The Steering Committee conducted its deliberations primarily in three meetings (February 28-March 1, April 26-27, and May 18-19, 2011). The first and third meetings were held in Washington DC, and the second in HAO, Boulder, CO.

Members of the SC participated either by direct attendance or by calling in. The SC was charged to address the three following topics:

- Review of the scope of Focused Science Topics, Strategic Capabilities, and Tools and Methods (*Section I*)
- Recommendations for 2011 Focused Science Topics (FSTs) (*Section II*)
- Recommendations for 2011 Strategic Capabilities (*Section III*)

## *I. Review of the Scope of Focused Science Topics, Strategic Capabilities, and Tools and Methods*

Any review of the scope of the various elements of the LWS TR&T Program should begin with the LWS TR&T Strategic Goals. These are:

Strategic Goal 1. *Deliver the understanding and modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth, Moon, Mars and throughout the solar system (Solar Storms).*

*Rationale*: Solar energetic particles and galactic cosmic rays pose major radiation hazards for space hardware and astronauts. Penetrating particle radiation adversely affects aircraft avionics and potentially the health of airline crews and passengers on polar flights. Communication and navigation systems are directly affected by major and sometimes sudden increases in the solar particle and XUV output leading to re-routed polar flights, GPS outages, and spacecraft anomalies. This goal supports NASA's Vision for Space Exploration and the elements of our national communication, navigation, and transportation infrastructure whose operations are impacted.

Strategic Goal 2. *Develop a fuller understanding of how and to what degree variations in the Sun's radiative and particulate outputs will in conjunction with other forcing factors affect regional and global climate in the present century (Sun-Climate*).

*Rationale*: One of the major challenges we face today is global climate change, which is driven in part by the variable Sun. The influences of the Sun and its 11-year cycle are readily apparent in global and regional averages of air and sea temperatures. What is yet uncertain is the degree to which solar variability has affected the climate of the Earth on longer time scales of decades, as well as the physical mechanisms that could explain the reported evidence. In particular, this goal addresses the role(s) that the Sun has played in climate during the documented global warming of the last 100 years, and the extent to which variations in solar inputs may enhance or diminish the projected heating due to enhanced greenhouse gases in the atmosphere.

Strategic Goal 3. *Deliver the understanding and modeling required for effective forecasting specification of magnetospheric radiation and plasma environments (Near-Earth Radiation).*

*Rationale*: National infrastructures are increasingly dependent on satellites orbiting Earth. With advances in miniaturization these systems are becoming more sensitive to variations in their space environment. This goal aims to inform the space technology developers and to protect these assets through improved characterization of magnetospheric particle populations and electric and magnetic fields through their full range of variations. A part of this endeavor is an understanding of the physical processes responsible for these variations and especially for their extremes.

Strategic Goal 4. *Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below (Ionosphere-Thermosphere).*

*Rationale*: The upper atmosphere and ionosphere is central to a number of space weather effects, including anomalous satellite drag, GPS position errors, radio blackouts, radar clutter and geomagnetically induced currents (GIC). Models of this region are becoming increasingly detailed and realistic to the point where they can provide guidance in both orbit and operations planning and designing affected systems. Moreover, this region of the space environment is amenable to data assimilation into models, allowing active forecasting.

It is the sense of the SC that major changes in the scope of the Focused Science Topics (FSTs), Strategic Capabilities, and Tools and Methods should not be undertaken without the comprehensive review recommended by the 2010 SC. The present SC does not recommend any changes in the Tools and Methods element, and recommends minor but important changes in the scope of the FSTs and Strategic Capabilities, discussed below.

### *Scope of Focused Science Topics*

The Focused Science Topic (FST) option presents proposers with an opportunity to work as contributors to a team effort on a targeted subject with the aim of achieving a higher level of progress or closure toward an LWS goal. The maximum duration of these awards is typically 4 years. NASA desires a balance of research investigation techniques for each Topic, including theory, modeling, data analysis, observations, and simulations. Any individual proposal does not need to include all techniques. Given the submission of proposals of adequate number and merit, up to eight selections will be made for each FST. Once selected, these investigators will form a team in order to coordinate their research programs. One of the Principal Investigators (PIs) will serve as the Team Leader for the FST for which (s)he proposed and will receive supplemental funding, as necessary, to support costs associated with these duties. Proposers are encouraged to propose to act as a Team

Leader and, if they do so, should include a brief section in their proposal describing how they would lead the team effort. Up to one extra page in the proposal is allowed for this proposed effort. All proposers for FSTs should include sufficient travel funds in their proposed budgets to cover two team meetings per year to be held on the U.S. coast furthest from their home institutions. See Instructions for TR&T Focus Team Members and Leaders at (http://lws-trt.gsfc.nasa.gov/focus_team_instructions.pdf) for full details of responsibilities. While the primary evaluation criteria remain unchanged (see *ROSES Summary of Solicitation*, Section V(a), and the *NASA Guidebook for Proposers*, Appendix C.2), the criterion for relevance includes relevance to one of the FSTs as an essential requirement for selection within this component. In order to be compliant to this ROSES element, each proposal submitted must contain a section, entitled “Proposed Contributions to the FST Effort” and identified in the proposal’s table of contents. Failure to include this section will result in the proposal being judged non-compliant, and the proposal will be returned. This section must include the following items:

- The relevance of the proposal to the objectives of the FST
- The potential contributions (including but not limited to novel understanding of physical mechanisms, simulation results, and data sets) from the proposed effort to the Focus Team effort
- Metrics and milestones for determining the successful progress and outcome of the proposed research.

Since each Focus Team has to produce a joint statement of work (SOW) specifying its deliverables, success criteria, and milestones, the mandatory section described here can serve as a beginning point for this SOW.

The *NASA Guidebook for Proposers* states "NASA strongly encourages PIs to specify only the most critically important personnel to aid in the execution of their proposals." LWS further emphasizes that Focus Teams will be formed from individual proposals selected in a FST. Therefore, individual proposals do not need to tackle the whole problem, but can instead seek to solve a piece of the problem.

***Remark***: The only new element in the description above is the recommendation that typical maximum duration of the awards should be 4 years instead of 3-4 years. It is the sense of the SC that mixing the duration of awards in a Focused Science Team, with some awards lasting 3 years and others lasting 4 years (pending a mandatory review after 3 years), hinders synchronization and planning of Team activities. In some cases, if it is determined that the 3-year awards should be extended by another 1 year with additional funding, the awardees as well as the Program Scientists have to go through another process of review which places an extra burden on awardees, reviewers, as well as the Program Scientists. The sense of the SC is that this should be avoided, if at all possible.

### *Scope of Strategic Capabilities*

The aim of the TR&T program is to produce scientific understanding targeted at our ability to model, specify and forecast solar variability effects on climate, stratospheric ozone and near-Earth space weather. Although the development of operational models is not a direct goal of the TR&T program, TR&T does require mechanisms for transferring knowledge as well as empirical and physics-based models of the Sun-Earth system to potential users of these products by developing critically needed capabilities. Users include other scientists, policy makers, NASA, US agencies charged with developing operational models as well as commercial interests such as the airline and power industries. It is expected that the product(s) will be made widely available to the community, for instance, by delivery to the CCMC.

The principal objective of a Strategic Capability within the TR&T program is to support areas that have reached a level of maturity whereby investment in teams of theorists, computational physicists, and observers can lead to rapid and transformational progress in developing empirical and physics-based predictive capabilities. The SCs can be up to 5-year efforts that assimilate the results from earlier FSTs or be separately identified. Examples include but are not limited to the bringing together of multiple mature physics-based modules to form a new critically needed capability, the development and implementation of fundamental science and/or novel computational algorithms in a comprehensive model, and/or the development of methods for constructively utilizing vast amounts of data towards a predictive capability. There is also a recognized need for transformational investments in the physical and computational capabilities of the underlying models, integrate across physical domains, and reach out across wide ranges in scales. This will not only create new knowledge and products of demonstrable value, it will be of direct benefit to society as we work towards more realistic forecasting of space and terrestrial weather and climate, capitalizing on advances in computer architecture and data storage to increase the capability of our workforce.

***Remark***: While retaining all of the present features of Strategic Capabilities, the SC recommends an augmentation of this category to include an explicit emphasis on computational physics/algorithms relevant to theory as well as data analysis and assimilation in heliophysical science. It is the sense of the SC that such a recommendation is consistent with the white paper that emerged from the community-wide Workshop on Advanced Computational Capabilities for Exploration in Heliophysical Science (ACCEHS), held on August 16-18, 2010 at NCAR in Boulder, Colorado (http://www.hao.ucar.edu/ACCEHS/). The Workshop brought together over 80 scientists in heliophysical science, as well as experts from the climate and computer science communities.

### *Scope of Tools and Methods*

The Tools and Methods component supports studies that deliver tools and/or methods that enable critically needed science advances. The maximum duration of these awards is 2 years. Examples include (1) the development of new empirical methods or analysis techniques, such as local helioseismology, that can be used to forecast solar, interplanetary, and geospace activity, (2) the development of new feature recognition or artificial intelligence (AI) algorithms that can advance predictive capabilities for the LWS system, and (3) the development of software tools that can identify, retrieve, assimilate, and/or portray data in order to model results from different sources for LWS research and forecasting objectives. Tools that address the four LWS TR&T strategic goals will be especially welcome.

A deliverable product(s) and delivery site must be specified along with a delivery date. The deliverable product can be, for example, a stand-alone product or a web application, and must be delivered to a LWS approved repository/server such as the Community Coordinated Modeling Center (CCMC; http://ccmc.gsfc.nasa.gov/), an existing Heliophysics virtual observatory (VxO), solar soft repository, or a mission site. The delivery date must be during the final year of work with enough time left to support appropriate documentation and handover to the CCMC/VxOs/solar soft/mission to insure longevity and to enable its independent use by the scientific community. All tools will be listed with links from the LWS TR&T web site (http://lws-trt.gsfc.nasa.gov). Furthermore, the Proposal Summary that is submitted at the NSPIRES website must include explicit language stating the following:

*Deliverable:* What will be the tool or method?
*Delivery Site:* Where will it be delivered (e.g., CCMC, data center, mission site)?
*Schedule:* When will it be delivered?

Proposals that do not include the Deliverable, Delivery Site and Schedule explicitly in the Proposal Summary will be deemed non-compliant and will not be reviewed.

***Remark***: The SC recommends no change in the present scope of Tools and Methods.

## ***II. Recommendations for 2011 FSTs***

The SC has devoted a considerable amount of time in developing suggestions for 2011 FSTs. Suggestions were solicited by the SC during the Town Hall at the 2010 Fall AGU Meeting, and by means of multiple announcements through the SPA Newsletter and SolarNews. Quite a few of the topics recommended below had their genesis in ideas put forward online and by e-mail by members of the community, which reinforces the importance of community participation in the process. The following is a list of the recommended FSTs, divided under the headings of the four Strategic Goals given in Section I. (The order is not prioritized.)

## *IIA. Recommended FSTs for Strategic Goal 1 (Solar Storms)*

### Flare Dynamics in the Lower Solar Atmosphere

*Target Description*:

The solar chromosphere (generally speaking) marks sudden changes in several basic physical parameters, such as opacity, collisionality, density, or plasma beta. Flares represent drastic perturbations of this complicated system as a test pulse, with interesting implications for particle acceleration, radiative transfer, and magnetic restructuring. The "impulsive phase" marks the epoch of most intense energy release and the main flare nonthermal effects, and coincides with the acceleration phase of the associated CME. We now have major new observational and theoretical tools that may make substantial progress possible in understanding this system. The key process in the impulsive phase is the intense acceleration of non-thermal particles, recognized via their hard X-ray and gamma-ray bursts.

As a part of this activity, the apparently connected phenomena of the CME launch, the white-light flare (as observed also in the total solar irradiance), and the newly recognized "sunquake" seismic signature in the solar interior may be tied together. These studies can take advantage of the stepwise changes in the photospheric line-of-sight magnetic field, which new observations (*Hinode* and *SDO*) will be able to extend to the full vector field. The changes in the magnetic field at the time of the impulsive phase must directly reflect the physical nature of the flare/CME instability, since they reveal the flow of energy from the field into particles, flows, and heating.

The complexity of the chromosphere and its phenomenology make this a good subject for a team approach, incorporating modeling efforts at several levels (MHD, radiation transfer, plasma) as well as diverse observational material requiring different specialists. The key observations from space include those from *RHESSI*, *Hinode*, and *SDO*. It is likely that only a subset of the tasks listed below can be tackled, but the effort should nevertheless take a broad view of the processes involved. Success in understanding the energy transformations and momentum balance of the impulsive phase should help substantially in characterizing the initial development of a CME and the global coronal processes associated with it.

*Goals and Measures of Success*:

- Progress in understanding the transport of energy and momentum into the interior from the solar atmosphere (sunquakes).
- Progress in understanding high-energy phenomena in the impulsive phase of a flare.
- Extension of the photospheric field changes now known from the line-of-sight field to the full vector field.
- Progress in revising the standard thick-target model of the flare impulsive phase.

*Types of Investigations*:

- The characterization of sunquake signatures in terms of energy and momentum, and their relationship with the flare impulsive phase.
- The application of plasma-physics tools to the chromosphere, in which (for example) ion-neutral coupling may dominate the electrodynamics and Hall currents.
- The analysis of footpoint emissions, relating hard X-rays and gamma rays with visible/UV continuum and EUV spectra, to understand energy transport.
- The observation and characterization of flare seismic waves in order to distinguish among different mechanisms for corona/interior coupling.
- The exploration of Alfven waves in the kinetic limit, in a dense, partially ionized medium, as a source of particle acceleration.
- The development of innovative techniques for 3D magnetography of active regions (possibly including stereoscopic observations).
- Investigation of the anomalous 511-keV line widths observed by *RHESSI*, which suggest particle trapping at transition-region temperatures.

## Understanding Electron Acceleration and Its Connection with Energetic Protons in SEP Events

*Target Description*:

Compared to recent progress in understanding and modeling proton and ion acceleration at CME-driven shocks in large SEP events, there have been relatively fewer efforts tackling electron acceleration to high energies in these events, although there is a large database providing evidence for electron acceleration through radio and in-situ particle observations. Electrons should be part of a complete picture and an integral consideration for the energy budget of the SEP production, but the mechanisms for accelerating electrons have been difficult to model. Observations have shown that high-energy (> 0.1 MeV) electrons associated with large SEP events have close correlation with high-energy protons, and can be used to provide an early warning for the approaching proton radiation hazard. The underlying physical connection between electron acceleration and proton/ion acceleration in large SEP events has been a challenge to our current understanding of the origin of these events. Shocks, particularly quasi-perpendicular shocks, may play an important role in electron acceleration. In this case, electron observations and modeling can provide a tool for diagnosing shock geometry in a CME event, which has also been proposed as an important factor in the variability of ion spectra and composition. Other electron acceleration mechanisms also exist, associated with reconnection in a CME-associated current sheet, with the possible presence of contracting magnetic islands. Solar type II and type III radio bursts give strong observational evidence for electron acceleration in solar transient events. Although the accelerated electrons that produce these bursts are believed to be of lower energies, the acceleration processes of these electrons may provide a crucial link to a complete picture of electron acceleration in solar eruptions. This focused topic aims to stimulate breakthroughs in understanding electron acceleration in SEP events as an integrated picture of particle acceleration with protons and ions.

The electrons that enter into the acceleration processes are a constituent of the ambient corona before an eruption occurs. There may be a need for 'seed electrons', which could come from various origins such as coronal heating, solar wind acceleration, flares/CMEs, and small-scale reconnection events (e.g. microflares and nanoflares). Therefore some basic understanding about the electron velocity distribution function (VDF) and intensity at the acceleration site is essential for constraining electron acceleration models and providing insights into the variability of high energy electrons. It is known that the electron VDF measured at 1 AU exhibits components of core, halo and strahl that vary with other solar wind properties. However, the electron VDF in the corona is not known. How much it deviates from thermal distribution, how it varies with solar and solar wind parameters (such as plasma beta, density, and speed), and how it evolves during transport to 1 AU are also rarely investigated. This poses a need for further efforts in modeling the electron VDF and its variations in the ambient corona, by either theoretical or empirical means. Such efforts can also facilitate the understanding of the data anticipated in the upcoming Solar Probe Plus and Solar Orbiter missions.

*Goals and Measure of Success*:

- Predict the intensity and energy spectrum of accelerated electrons produced in CME-driven shocks, reconnection, or by other mechanisms that are consistent with observations.
- Predict the correlations between energetic protons, ions and electrons that are consistent with observations.
- Determine the processes that generate the electron seed population, if needed.
- Predict the intensity or shape of the electron VDF in the corona, its variation with solar parameters, and its transport in the heliosphere that are consistent with observations

*Types of Investigations*:

- Theories and models for electron acceleration (e.g. waves, turbulence, reconnection, shocks).
- Models that establish or predict the relations between high-energy protons and electrons.
- Theories and models for generating the seed population of suprathermal electrons or predicting the intensity or shape of the electron VDF in the corona, its variation with solar and solar wind parameters, or its transport in the heliosphere.

- Data analyses of SEPs (electrons, protons and ions), CMEs (e.g. energetics, shock parameters), solar flares and radio bursts that are focused to provide empirical constraints and inputs for the acceleration processes in theories and models.
- Solar and solar wind data analyses that are focused to investigate the variability of the electron VDF in the corona and serve as constraints and inputs for theories and models.

---

## Combining SDO, STEREO, and *In Situ* Data With New Strategic Capabilities to Understand the Sources of Heliospheric Dynamics

*Target Description*:

The degree to which heliospheric variations and dynamics form *in situ*, rather than simply at the Sun, remains controversial. This poses a challenge for understanding the source of solar wind dynamics on all but the largest spatial and temporal scales. For example, ICMEs are due to large-scale dynamics at the Sun, however, it is unclear which substructures within ICMEs form *in situ*, and which substructures are a fundamental part of the CME formation and launch. By understanding which variations in the heliosphere are directly linked to variations at the Sun, we can understand their source. Do coronal jets/plumes become pressure-balance structures in the heliosphere? Does the outward flowing plasma observed at the periphery of active regions feed the solar wind? Are the variations surrounding CIRs due to the shock formation, or were they already present in the solar wind and merely processed by the shock? Does the 'spaghetti' flux-tube structure of the solar wind relate to solar granulation or to coronal flux tubes?

Currently there is an unprecedented opportunity to combine *SDO*, *STEREO*, and *in situ* data to understand how, and from where these and other dynamics in the heliosphere originate. The *STEREO A* and *B* spacecraft are currently separated 180 degrees, each making a 90-degree *STEREO*-Sun-Earth angle. The result of this unique configuration is that the plasma observed in the STEREO coronagraphs and inner HI instruments will be directed towards the Earth. Therefore, L1 spacecraft such as *ACE* and *Wind* are positioned ideally to measure this plasma *in situ*. SDO, with its extraordinary temporal and spatial resolution and coverage, is positioned perfectly to observe face-on the structure and dynamics just before they enter the *STEREO* coronagraphs field of view. Additionally, the Messenger spacecraft was inserted into orbit around Mercury on March 17th, 2011, potentially providing *in situ* measurements in the inner heliosphere. Mercury (and the solar wind plasma surrounding it) is in the field of view of the inner *STEREO* HI instruments. When the Sun, Mercury and Earth are in line (this occurs for a couple of days, approximately every 90 days – Mercury's orbital period) the plasma observed in the coronagraphs will flow outwards towards Mercury, where the *MESSENGER* magnetometer data will provide *in situ* inner heliospheric measurements.

Another compelling argument for the timeliness of this Focused Science Topic is that the modeling capabilities required for interpreting the unique data sets described above are now coming on line. As part of the Strategic Capability TR&T element, two next-generation 3D models of the coupled corona-heliosphere system will be delivered to the CCMC next year. These are precisely the tools that will be needed to realize the advances in understanding promised by the observations. Furthermore the detailed 3D observations from *SDO* and *STEREO* will be ideal for validating and verifying the models.

Combining disparate data sets with models has already provided valuable insight into the evolution and dynamics of large scale structures such as ICMEs and CIRs as they propagate through the heliosphere, and can be applied to smaller-scale dynamics in the solar wind. The method involves first, connecting phenomena (and corresponding substructures) observed *in situ* to the SECCHI HI images, through the SECCHI coronagraphs, down to their solar origin using *SDO* images and *Hinode*/EIS spectra. Second, connecting phenomena at the Sun observed in *SDO* through the SECCHI coronagraphs and the SECCHI HI imagers to *in situ* measurements. Only now are the *STEREO* spacecraft positioned to take full advantage of this technique, and only now are the coronagraphs imaging plasma that is truly directed at the Earth. Incorporating *SDO* data as well as the *in situ* data provide insights into the physical mechanisms that created the dynamics and variability. Finally, it should be noted that in addition to raising our understanding of heliospheric dynamics to a new level, this FST will pave the way for the next generation of LWS missions, *Solar Orbiter* and *Solar Probe Plus*.

*Goals and Measures of Success*:

The overarching goal is to combine the exceptional, massive amount of observations from our most recent and powerful solar observatories, *STEREO* and *SDO*, with the new LWS Strategic Capabilities to understand dynamics in the heliosphere. The measure of success is the ability to map transient features observed in the heliosphere, either *in situ* (with *MESSENGER/ACE/Wind*) or remotely (with *STEREO* HI) down through the high corona (with the *STEREO* coronagraphs), low corona, chromosphere and photosphere (with *SDO* and *Hinode*).

*Types of Investigations*:

- Use *SDO*, *STEREO* and other imaging capabilities to follow features both radially outward and inward. Observe with the highest possible accuracy the development and propagation of transients, from the chromosphere out to 1 AU. Relate their development to observations of the underlying photosphere with *SDO* and using *Hinode*/EIS for elemental abundance measurements.
- Use *ACE/Wind* and other *in situ* capabilities to investigate the corresponding plasma, energetic particle (strahl), plasma composition, charge state (freeze-in temperatures), and magnetic field structure dynamics of structures once they

reach 1 AU. Compare these *in situ* observations with current theories of formation of various types of solar wind dynamics.
- Use *MESSENGER* magnetometer data as an *in situ*, inner heliospheric probe to understand detailed magnetic structure of features observed in HI. Use state-of-art models to predict the dynamic coupling of the corona to heliosphere.
- Use the observations to validate and refine the models.
- Develop theories for the dynamic corona-heliosphere coupling.

## Coherent structures in the solar wind and their effects on the transport of solar energetic particles

*Target Description*:

Coherent structures, including tangential discontinuities (TDs), rotational discontinuities (RDs), magnetic holes, density holes, current sheets, etc., are ubiquitous in the solar wind. These structures are a major source of solar wind MHD turbulence intermittency. The origin of these structures are presently unknown. They could be dynamically generated as a consequence of the non-linear interaction of the solar wind MHD turbulence. Indeed, numerical simulations have shown that 2D structures can spontaneously emerge in an original homogeneous background. However, theoretical work on how these structures generate and evolve in a highly anisotropic solar wind is still lacking. On the other hand, there are proposals that some of these structures may be relic structures statically advected with the solar wind. For example, tangential discontinuities may represent the boundaries of flux tubes. One potential way to shed light on the origins of these structures is to investigate the statistical properties of these structures and their radial evolution. In that regard, using multi-spacecraft including Messenger, ACE/WIND and Ulysses to examine these structures are highly desirable.

These structures can also affect the transport of solar energetic particles (SEPs). For example, the concept of flux tubes has been originally proposed in understanding the modulation of cosmic ray in 1960s. They may also the cause of the observed "drop-out" phenomena in solar energetic particle events. Recent simulations have shown that these structures can greatly affect the perpendicular diffusion of energetic particles. A proper understanding of energetic particle observations (time intensity profile and spectra) in SEP events by multiple spacecraft observation (e. g. STEREO A and B and ACE/WIND) would therefore require a understanding of how energetic particles propagate with the presence of these structures.

*Goals and Measures of Success*:

The goal of this Focused Science Team is to advance our understanding of coherent structures (discontinuities) in the solar wind, including their statistical properties, their radial evolution, and their generation mechanism as well as their effects on the transport of solar energetic particles. Observational studies from possible multi-spacecraft (Messenger, ACE/WIND, Ulysses, STEREO), as well as theoretical and numerical simulations are all welcomed.

Success of this team will be measured by: the improvement in our understanding of how coherent structures (discontinuities and current sheets, etc.) are generated in the solar wind, what are their properties and their effects on solar energetic particle transport.

*Types of Investigations*:

- Multi-spacecraft observations to characterize the properties of various coherent structures in the solar wind. Including for example, their radial evolution, their occurrence rate as a function of solar wind properties and their effects on the power spectra and structure functions of the solar wind MHD turbulence.
- Theoretical work and numerical simulations addressing the generation mechanism and evolution of these structures in the solar wind. In particular, how these structures are generated in a highly anisotropic solar wind, and what are the life times of these structures.
- Theoretical work and numerical simulations on the effect of these structures on energetic particle transport in the solar wind. In particular, how these structures can affect particle perpendicular diffusion in SEP events and how do these compare with multiple spacecraft (ACE/WIND, STEREOs) observations.

## Maximizing Science Return from Solar Wind Composition Data

*Target Description*:

The heliosphere is filled with solar wind, with speeds ranging from below 400 km/s to above 700 km/s. The fastest solar wind (>700 km/s) is primarily associated with large regions of predominantly unipolar magnetic field – coronal holes. Near solar minimum the fast solar wind is usually confined to the two polar coronal holes. The slow solar wind (~400 km/s), on the other hand, is usually confined within a band associated with the heliospheric current sheet that separates the two polarities. This separation was clearly demonstrated by *Ulysses's* first orbit.

*Ulysses's* first orbit further showed that there is a dramatic difference between the ion compositions of these two types of wind streams. Fast solar wind is characterized by ionic charge states that are indicative of relatively cool conditions in the corona. The slow wind exhibits ionic charge states indicative of hotter conditions in the corona and also has an elemental composition that is fractionated with respect to the photosphere, favoring ions with low first-ionization-potential (FIP), a phenomenon not strongly observed in the fast wind.

*Ulysses's* second orbit, passing over the solar poles near the maximum of the 11-year activity cycle, showed alternating high- and low-speed streams at all latitudes. *Ulysses's* third orbit, occurring during the recent unusually extended solar minimum, had the same large-scale structure as the first orbit, but with subtle (but distinct) different compositional signatures that imply a significantly cooler corona. Moreover, in-ecliptic solar wind observations show plenty of examples that solar wind with similar bulk flow properties can have very different composition signatures.

It is timely, given the wide variation in the continuous solar wind composition measurements in the past two solar cycles, and the non-selection of an Ion Composition Experiment for Solar Probe+, to call for a Focused Science Topic to maximize the science returns from *existing* Solar Wind Composition data: *ACE*/SWICS, *Ulysses*/SWICS, *STEREO*/PLASTIC, *Wind*/SMS, and *SOHO*/CELIAS data, so as to develop a coherent mechanism for fractionation of solar wind composition, heating and acceleration of solar wind ions, and its temporal and spatial variations. To explain the origins of the differentiated solar wind completely, it is key to characterize and understand the bulk flow and elemental/ion composition *simultaneously*. This is a quintessential System Science investigation: given that the energy that heats the corona and drives the wind derives from photospheric motions and is channeled, stored, and dissipated by the magnetic fields that emerge from the photosphere and structure the coronal plasma, changes in solar wind properties must ultimately stem from processes in, or below, the photosphere. Therefore it is also key to combine observations of different layers of the solar atmosphere that manifest these (sub-)photospheric processes for interpreting and understanding the variations in solar wind composition.

*Goals and Measures of Success*:

- To develop self-consistent models of coronal heating, solar wind acceleration and ion-neutral fractionation that are consistent with solar wind composition data and associated solar observations.
    - Are the fast wind and slow wind driven by radically different processes, or is a continuous range of bulk flow properties possible?
    - To understand the causes for variations in solar wind composition.
- To develop models and techniques to prepare for, and that will enhance the science return of, the *Solar Orbiter* and *Solar Probe+* missions. Explaining the solar wind ion composition by means of physics-based models of coronal heating and acceleration of the nascent solar wind. For example:
    - Is solar wind acceleration decoupled from coronal heating?
    - What processes/characteristics in the solar atmosphere determine the variations in the solar wind ion composition?
- Explaining the solar wind elemental composition in the solar wind by means of physics-based models for ion–neutral fractionation.

- Solar observations (e.g. magnetic, spectroscopic or dynamic properties) or empirical models that can relate to and interpret the spatial or temporal variations in the solar wind composition.
- Explaining the long-term variations in composition/ velocity dependence signatures over the solar cycle, and, in particular, in the recent unusual solar minimum.
- Explaining the short-term variations in composition over individual solar wind streams (down to flux tubes/ instrument cadence limit). This may include *ACE-STEREO* correlation studies.
- Preparing for the upcoming launch of *Solar Orbiter*, and mitigating the lack of an Ion Composition Experiment on *Solar Probe+,* by developing models of solar wind thermal and suprathermal elemental/ion composition properties and ion VDFs in the inner heliosphere.

## *IIB. Recommended FSTs for Strategic Goal 2 (Sun-Climate)*

### Studies of Solar Dimming Through Measurement of the Irradiance Contribution of Small Photospheric Magnetic Flux Tubes and of Their Depletion During Extended Solar Activity Minima

*Target Description*:

The single most important challenge to Sun-climate research is: "Could the Sun have dimmed sufficiently to have caused the 15th – 17th century cooling of the Earth known as the Little Ice Age?" This is the problem, given major prominence by Jack Eddy in 1976, which continues to provide the main motivation underlying Sun-climate studies. Its importance is strengthened by more recent evidence from ocean sediments that similar activity – correlated cooling occurred on a millennial time scale throughout the Holocene.

Removal of facular flux tubes from the quiet magnetic network presently offers the simplest path to climatically significant solar dimming below normal quiet Sun levels of total solar irradiance (TSI). Recent radiometric and photometric analyses suggest that the TSI contribution per unit area of facular flux tubes *increases with decreasing facular diameter*. This interesting finding suggests that removal of the progressively smaller flux tubes remaining at the prolonged Maunder and Spörer minima of the 15th – 17th centuries, might have decreased TSI by 2-4 times more than estimated in the past from linear extrapolation of chromospheric activity indices. Even partial removal of the network might then enable a TSI decrease sufficient to explain the Little Ice Age, while still preserving sufficient photospheric magnetism to explain the weakened 11 yr. cycle observed in $^{10}$Be during the Maunder Minimum.

Missing at present are secure understandings of i) the TSI contribution of quiet–Sun photospheric flux tubes down to the smallest sizes that might conceivably influence TSI at a climatically significant (>0.2% ) level; ii) the processes of field generation and dissipation that determine the number and size spectrum of these flux tubes during prolonged activity minima lasting several decades.

*Goals and Measures of Success*:

- To measure the radiance of network and intra - network flux tubes over a broad range of heliocentric angle and wavelength.
- To measure the size distribution function of such flux tubes.
- To study their internal dynamical structure and origin.
- To study their sources and sinks, taking into account the possibility of shallow dynamo activity operating even at prolonged low activity levels.
- Thus to improve estimates of the filling factor, size distribution and contribution to TSI variation, of network flux tubes during prolonged solar activity minima.

*Types of Investigations*:

- Analysis of magnetic and continuum data from e.g. *Hinode*, *SDO* HMI, and high – resolution ground based facilities, to measure the radiance and size distribution of network flux tubes at the highest achievable (sub–arc-second) angular resolution.
- Extend the above observations to cover a sufficiently broad range of near–UV, visible and near–IR wavelengths to calculate their contributions to TSI.
- Simulate the formation and decay of the network flux tubes, the origin and size dependence of their enhanced TSI contribution, and of its size dependent relation to their cross – sectional area.
- Simulate their sources and sinks within the context of current dynamo theory with particular attention to the possibility of a minimum level of photospheric flux attributable e.g. to a component of dynamo activity that might be independent of the 11 yr. cycle.
- Compare the above findings with statistics on e.g. $^{10}$Be modulation and auroral observations during the 15th – 17th centuries. Combine the above investigations into an improved estimate of solar dimming during the Little Ice Age.

---

## Critical Assessment of Dynamo Models

*Target Description:*

The origin of solar activity lies below the photosphere in the internal flows that generate the magnetic field and determine the properties of the dynamo. Between these causative flows and the effects in the solar atmosphere and heliosphere lies a chain of physical processes and interfaces that are complex and far from understood. Many such processes have been studied in detail, but the connections between them are largely unexplored. We must advance our understanding of these couplings and incorporate them in improved physics-based models in order to make reliable forecasts of the solar activity cycle.

Subsurface magnetic field can be generated in the tachocline at the base of the convection zone, in the body of the convection zone, near the surface in a shear layer, and by turbulence. In kinematic dynamo models, the interplay between the large-scale internal flows of differential rotation, meridional circulation, kinetic helicity, and turbulent magnetic diffusion results in the transport of magnetic flux and helicity within the convection zone and subsequent concentration of the field to the point that it becomes buoyant and emerges at the surface. Kinematic dynamo models have achieved significant success, but some critical ingredients are poorly constrained below the surface and incompletely understood even at the surface. Questions that need to be investigated include:

- What is the nature of interior flows, and how do they determine the sunspot cycle period?
- Are subsurface flows from helioseismology consistent with observed flows in the photosphere?
- How is magnetic helicity generated and transported throughout the convection zone?
- How does the generation of kinetic and magnetic helicity below the photosphere affect the emergence and evolution of active regions and dynamo itself?
- Do observed poloidal fields arise only from the surface transport of active-region fields?
- Are models of photospheric flux transport measurably improved by including subsurface flows or different models of turbulent magnetic diffusion?
- How do additional mechanisms of flux transport (for example turbulent magnetic pumping) affect the observed properties of the dynamo?
- Can critical elements of the kinematic dynamo picture be constrained through observations of other stars?

*Goals and Measures of Success:*

The goal of this FST is to better understand the coupled magnetic and kinematic processes in the solar interior, photosphere, and corona and to use this knowledge to improve the predictive potential of dynamo models. Metrics of success include improved agreement between observed and modeled surface magnetic flux that better incorporate helioseismically determined subsurface properties and therefore have fewer free parameters, and the ability to account for the observed range of cyclic behavior in solar-type stars.

The *Solar Dynamics Observatory* produces a wealth of pertinent data necessary to address this FST; for example, HMI will provide high-degree helioseismology and simultaneous high-cadence vector magnetic field observations in the photosphere. The broad and systemic nature of the proposed research requires a coordinated approach that spans multiple areas of expertise but retains a focus on critical elements of the *solar* flux-transport dynamo picture.

*Types of Investigations:*

- Studies of the relationship between helioseismic inferences of internal flows and observed vector magnetic fields in the photosphere, including detailed analysis of polar field measurements,
- High resolution MHD models of convective turbulence at various depths in the convection zone, including surface effects such as supergranular flows, to yield better estimates of turbulent magnetic diffusion for inclusion in flux transport models, and the generation and transport of magnetic helicity at various depths in the convection zone.
- Global MHD studies of various flux generation and transport mechanisms within the convection zone.
- Kinematic dynamo models that can explore a wide range of parameters using both solar and stellar observations as constraints.
- Stellar observations focused on measurable properties that can constrain the solar kinematic dynamo picture—e.g., cycle period, rotation rate, differential rotation, latitude distribution of activity, and asteroseismic properties.

## *IIC. Recommended FSTs for Strategic Goal III (Near Earth Radiation)*

### **Interaction between the magnetotail and the inner magnetosphere and its impacts on the radiation belt environment**

*Target Description:*

As plasma from the near-Earth magnetotail is transported in to the inner magnetosphere, it energizes and directly impacts the structure and dynamics of the entire inner magnetosphere. For example, the resulting enhanced plasma pressure drives currents that connect to the ionosphere and that severely distort the electric and magnetic fields of the entire inner magnetosphere. In turn, the resulting dynamics of the magnetic fields and the altered wave environment are key players in controlling the dramatic variability of the outer electron radiation belts. Therefore, understanding how plasma is energized and transported in to the inner magnetosphere is one of the missing links in our ability to predict near-Earth space weather. Recent observations and modeling have demonstrated that inward plasma transport in to the ring current region may occur through finer-scale instabilities and not by a simple wide front of earthward plasma convection. Global and in-situ observations have demonstrated that O+ can dominate the plasma pressure through efficient non-adiabatic energization processes only described by single particle theory. The responsible processes appear to be much more complicated than previously thought in that they appear to be a mix between MHD and kinetic (particle) phenomena – a modeling capability that is still maturing. Major uncertainties remain about the exact nature of these processes; when they occur and when one process dominates over the other. Numerical modeling efforts have recently started to combine the ability to model the global magnetosphere with kinetic and particle models of the ring current and inner magnetosphere, providing useful tools for studying these processes. Global and in-situ observations by missions such as *IMAGE, TWINS, Cluster, THEMIS* and in particular *RBSP* offers data relevant to these investigations and can provide global model validation.

*Goals and Measures of Success:*

The goal of this Focused Science Team is to advance our understanding of plasma acceleration and transport from the magnetotail to the inner magnetosphere by using observations and modeling. This effort builds upon the previously supported numerical model development activities and will utilize the observations made by several missions, but in particular the *RBSP* mission.

Success of this team will be measured by: the improvement in our understanding of plasma transport process; the development of detailed descriptions of the nonlinear interaction between low energy plasma transport, the ring current and its impact on the outer radiation belt; continued improvement of coupled numerical models of the inner and outer magnetosphere.

*Types of investigations:*

- Global and multi-point observations to characterize and investigate the energization and transport processes that lead to enhanced particle pressure in the inner magnetosphere
- Studies of potential plasma instabilities (plasma bubbles) responsible for the relevant plasma transport in to the inner magnetosphere
- Studies of how the plasma energization and transport impact the dynamics in the inner magnetosphere including
    - how the dynamics of the ring current affects the structure of the magnetic and electric fields
    - how the wave environment of the inner magnetosphere is altered
    - how the dynamics of the outer radiation belts are affected by the processes above
- Investigations on how inner magnetospheric state, e.g. ring current and convection electric field, affect the evolution of the magnetotail.

## Cross-Scale Magnetosphere-Ionosphere Coupling

*Target Description*:

Physical processes that characterize the flow of mass, momentum, and energy between the magnetosphere and ionosphere cover a wide range of spatial and temporal scales. Understanding these multiscale processes is fundamental to bridging the gap in understanding between large-scale magnetospheric dynamics associated with global current systems or large-scale flows and the ionospheric response that provides resistance to magnetospheric dynamics through ionospheric drag and mass loading of magnetospheric field.

The flow of energy to the ionosphere is mostly through the transfer of field-aligned Poynting fluxes over a wide range of frequency and spatial scales and acceleration of electrons. On a global scale, Poynting fluxes communicate plasma bulk motion to the ionosphere. However, significant Poynting fluxes are also carried by Alfvénic fluctuations, EMIC waves, and Lower Hybrid waves, and these processes are closely associated with ion outflows. How mass outflows can affect bulk motion and wave energization processes is of fundamental importance in order to advance a self-consistent description of the magnetosphere-ionosphere system.

When there are no field-aligned potential drops, flows in the magnetosphere and ionosphere are tightly coupled through a mapping of the convection electric field. However, field-aligned potential drops may be required to carry the currents required by the global magnetic configuration. Understanding when and where field-aligned potential drops occur is important because the electric fields in those regions cannot be mapped from the ionosphere to the magnetosphere and reflect a decoupling of the ionospheric and magnetospheric motion. In addition, the field-aligned potentials lead to intense particle energization.

Electron acceleration within field-aligned currents is also of fundamental importance to understanding the coupled magnetosphere-ionosphere system. Precipitating electrons can modify the ionospheric conductivity, which can ultimately feedback on a magnetospheric driver. The Knight relation is commonly used to estimate energetic electron fluxes within global models, but may not accurately reflect electron acceleration when electromagnetic turbulence is present. Therefore, observations and models that can describe the relationship between field-aligned currents and electron acceleration on multiple spatial and temporal scales are particularly important.

This focused science topic will necessarily require a coordinated effort on the part of ground- and space observers working in close collaboration with numerical and theoretical modelers. Several existing datasets can be brought to bear on this topic, including *Themis, RBSP, Cluster, DMSP, Polar, Fast, IMAGE*, SuperDARN HF radars, incoherent scatter radars, ground-based magnetometers and auroral imagers.

*Goals and Measures of Success*:

The goal of this focused science topic is to gain better understanding and predictive capability of multi-scale electromagnetic processes that couple the magnetosphere and ionosphere. These processes lead to field-aligned Poynting fluxes and electron acceleration resulting in mass, momentum, and energy flow from the ionosphere to the magnetosphere, which then affects the magnetospheric dynamics. Understanding of these processes would be verified using multi-scale observations from the magnetosphere, ionosphere, and acceleration region. The detailed coupling of magnetosphere and ionosphere electrodynamics along magnetic field lines will be verified.

*Types of Investigations*:

- Development of models to describe cross-scale coupling of electromagnetic waves and their affect on electron acceleration.
- Self-consistent descriptions of wave, electron precipitation, and ion outflow physics.
- Efforts to include M-I coupling physics in global simulation codes.
- Space- and ground-based observational studies of M-I coupling processes occurring along magnetic field lines on various spatial and temporal scales.
- Empirical characterization of the validity of the equipotential magnetic field line assumption as a function of location and geomagnetic activity.
- Observational studies of field aligned current, parallel potential drop, particle precipitation, and waves that can help illuminate the M-I coupling on various scales.
- Surveys or observations that identify the energy flows into the ionosphere, which in turn affect magnetospheric dynamics.

## Impact of Co-rotating Interaction Regions in the Solar Wind on the Magnetosphere-Ionosphere-Thermosphere System

*Target Description*:

The solar wind is controlled and organized by the Sun's three-dimensional magnetic field, and when coronal holes are present at low latitudes, high-speed streams (HSS) repeatedly intersect the Earth with frequencies that are harmonics of the solar rotation period. At the interface between high-speed and low-speed plasma, co-rotating interaction regions (CIR) are created, characterized by large variability in the interplanetary magnetic field. The combination of HSS and CIR drive geospace activity that is very different from the well-known impulsive forcing caused by coronal mass ejections. Interaction with the Earth's magnetosphere depends upon the magnitude, direction, and amplitude of fluctuations in the magnetic field. When the solar wind magnetic field is southward, and thus anti-parallel to the Earth's magnetic field, strong coupling results in flows of mass, momentum and energy into geospace from the solar wind. The key is the elevated level of magnetic field turbulence within the CIR, and continued oscillations during the transit of the HSS. Strong periodicities originating these processes have been observed in auroral and geomagnetic activity, in radiation belt changes, and in a range of upper atmospheric quantities, including ionospheric density, thermospheric density and composition, and radiative cooling rates. Thus, solar magnetic phenomena manifested by low-latitude coronal holes ultimately result in geospace impacts that extend downward into the Earth's atmosphere. Understanding how this process works is the target of this focused investigation.

*Goals and Measures of Success*:

The goal of this investigation is to determine how HSS/CIR drive changes in geospace, whether the magnetic oscillations in CIR are significant drivers of geomagnetic activity, and whether current theory and modeling can explain observed impacts and periodic fluctuations in the magnetosphere, ionosphere, and upper atmosphere. Space-based observations to be employed include solar wind and interplanetary field measurements, magnetospheric observations of the energetic particle population, ionospheric density distributions, and thermosphere density, composition, and radiation. The measure of success will be the ability to obtain closure between observations and models of short-term, solar-rotational, and solar-cycle variability in the solar wind plasma and in the near-Earth space environment.

*Types of Investigations*:

- Analysis of the impacts of high-speed streams and co-rotating interaction regions on the global structure of the magnetosphere, including the inner magnetosphere and plasmasphere.
- Studies of the effects on radiation belt and ring current response to HSS/CIR, including studies of plasma waves, and ULF oscillations.
- Modeling of magnetosphere-ionosphere-thermosphere coupling, including auroral variations and ionospheric disturbances.
- Data analysis of ionospheric changes from geomagnetic activity driven by HSS/CIR, and mechanistic studies of the causes.
- Modeling and data analysis of thermospheric fluctuations, including density, temperature, composition, and effects on the chemical-radiative energy balance.

## *IID. Recommended FSTs for Strategic Goal IV (Ionosphere-Thermosphere)*

### Dayside Magnetosphere-Ionosphere-Thermosphere System Response to Non-southward IMF

*Target Description:*

Recent observations and simulations show that the dayside magnetosphere-ionosphere-thermosphere (M-I-T) system responds vigorously to large excursions in the IMF $B_Y$ and $B_X$ components. Dayside energy deposition can rise by more than an order of magnitude above background in localized regions. Prolonged instances of large east-west excursions lead to neutral density upheavals (and satellite drag) that are sensed by accelerometers on low-earth orbiting satellites. The energy input can rival that deposited by nightside substorms. The most obvious instances of this behavior accompany the northward IMF phase of fast coronal mass ejections. The influence of solar wind speed and density and IMF fluctuations in these events has yet to be characterized. The role of energetic particle precipitation in these events is also not known. Initial MHD simulations suggest that flank and lobe merging during these $B_X$ and $B_Y$-driven are associated with and/or produce significant inter-hemispheric asymmetries.

The rise in Solar Cycle 24 provides a timely motivation to investigate the geospace drivers and physics behind these effects. Historical observations (e.g. *POLAR, IMAGE, FAST*) are available to complement current data from *Cluster* and *THEMIS*. The twin GRACE satellite mission has been extended until 2015, thus providing neutral density data. Ground based sensor networks and assimilative / empirical models provide information on ionospheric and thermospheric preconditioning and response. NSF's *AMPERE* satellite system will offer global field-aligned current monitoring Modelers have new capabilities, offering the ability to follow energy flow on multiple scales. Efforts in this area would strongly link to GGCM activities and community M-I-T coupling interests. The *SWARM* mission, due to launch in 2012, would benefit from and contribute to focus team efforts.

*Goals and Measures of Success:*

The goal of this FST is to determine the origins, physical processes, and effects of localized energy deposition in the dayside M-I-T system driven by variations in non-southward IMF and accompanying solar wind speed and density variations. Measures of success include:

- Quantifying the links between enhanced dayside field-aligned currents and Poynting flux, particle flux, and their impacts in the magnetosphere-ionosphere-thermosphere system in the presence of large in-the-ecliptic IMF, especially as they relate to enhanced neutral density, satellite drag, and ionospheric upwelling/outflow.

- Quantifying the influence of large in-the ecliptic IMF components under varying flow solar wind flow conditions on dayside M-I-T energy deposition.
- Determining the sensitivity of dayside ionosphere/thermosphere energy deposition to non-southward IMF compared to seasonally driven effects.
- Improving predictive capabilities of models in specifying dayside asymmetric energy inputs and their consequences to Earth's upper atmosphere.

*Types of Investigations:*

- Assessment of the roles of non-southward IMF excursions, variations in solar wind speed, and density perturbations, in modulating dayside energy deposition events.
- Determination of the effects of such events on satellite (and satellite constellation) location, pointing and control.
- Modeling of field-aligned current systems and their relation to Poynting flux and particle energy deposition for IMF $B_Z>0$ with large excursions of $B_Y$ and $B_X$ components.
- Modeling of inter-hemispheric asymmetries associated with excursions of IMF $B_Y$ and $B_X$ components, incorporating dayside ionospheric and thermospheric effects.
- Comparison and assessment of the roles of Poynting flux and particle flux in high-latitude dayside energetics.
- Modeling to establish the processes that lead to large Poynting flux and ionosphere/thermosphere heating under these conditions.
- Development of empirical relationships and indices to characterize energy input during non-southward IMF.

---

## Atmosphere-Ionosphere Coupling during Stratospheric Sudden Warmings

*Target Description:*

The dynamic coupling of the troposphere-stratosphere-mesosphere-ionosphere system is a complex interdisciplinary problem. Over the last three years our understanding of the relationship between the neutral atmosphere and ionosphere has been dramatically altered due to a research strategy focused on sudden stratospheric warmings (SSW) which collectively represent a compelling manifestation of coupling in the atmosphere-ionosphere system. Furthermore, SSW events are large-scale, well-defined, long-lasting, and have a predictable short term (several day) forecast and post-event duration. Recent studies suggest that a SSW couples all atmospheric layers from the ground to the thermosphere and from the poles to the equator and leads to significant perturbation in ionospheric electron density in excess of 50% from the mean state.. Understanding this key forcing mechanism including wave-wave interaction in the neutral atmosphere and neutral/plasma coupling has a large transformational potential for improved forecast of ionospheric space weather and a better understanding of the drivers of ionospheric variability, which are long standing frontier challenges in space physics.

However, while the occurrence of the initial SSW forcing is predictable, the subsequent effects of this forcing across the entire atmosphere-ionosphere system are not understood. In particular, while disturbances in the lower and middle atmosphere are related to planetary wave anomalies, coupling strength to upper atmospheric layers and the roles of planetary waves, tides, and gravity waves are less clear. Not much is known about the characteristics of nonlinear wave-wave interactions because they are difficult to analyze in observational data. Furthermore, a full understanding of SSW coupling into the ionosphere requires simultaneous observations in a variety of neutral and ionosphere parameters and models that fully account for neutral/plasma coupling and dynamics. Other uncertainties are the degree of influence on SSW events themselves by solar variability and solar proton fluxes, and the links that SSW processes may have on the Sun-to-weather connection through modification of planetary wave propagation in the stratosphere, mesosphere, and ionosphere.

Large space based data sets (observations from *EOS*, *TIMED* SABER, *Aura* MLS, *COSMIC*, C/NOFS, NCEP and EMCWF global stratospheric maps) along with ground based data sets (lidars, MF and meteor radars in the MLT region, incoherent scatter radars, magnetometers, GPS TEC maps) are available to address the problems in a needed mesoscale format. Recently developed comprehensive modeling tools (WACCM, NOGAPS, WAM) can be forced with assimilated data in the troposphere and stratosphere to recreate SSW events and analyze mesospheric-thermospheric responses. Focused modeling efforts using coupled whole atmosphere models are essential to interpret observations and assess impacts of driving processes on the MLT region and ionosphere.

It is timely to proceed with comprehensive studies as soon as possible. The long-term predictability (> 1 month) and frequency of occurrence of SSW events is affected by multiple external factors and is not understood. The last several years were marked by unusually high SSW activity. The reasons for this burst of SSW activity are not known, but it is still continuing as of the winter of 2010-2011.

*Goals and Measures of Success:*

The goal of this FST is to advance our understanding of dynamical coupling processes between the middle and upper atmospheres in both a theoretical and quantitative manner, and to lay the groundwork for future predictive capabilities in space weather and ionospheric variability. Success of this team will be measured by:

- Improved understanding of dynamo processes and energy transport from the lower atmosphere into geospace and from geospace to the lower atmosphere.

- Characterization of spatio-temporal variations in wave activity associated with SSW events (planetary waves, tides, gravity waves). Determination of tidal modes modulated during SSW events (solar/lunar, migrating/non-migrating, diurnal/semidiurnal/terdiurnal), planetary and gravity wave fluxes.

- Improved theoretical and observational understanding of key factors affecting the efficiency of atmosphere-ionosphere coupling (e.g. amplitudes of planetary waves, changes in zonal mean flow).
- Improved theoretical and observational understanding of the relative impacts of gravity waves and planetary waves in driving the atmospheric and ionospheric response to planetary waves originating in the stratosphere.
- Characterization of electrodynamic and ionospheric signatures associated with SSW and improved understanding of key mechanisms responsible for these signatures.

*Types of Investigations:*

- Observational investigations of planetary wave activity, tidal activity, and gravity wave activity in the stratosphere-mesosphere-ionosphere before, during, and after SSW.
- Observational investigations of changes in the dynamics in the stratosphere, mesosphere, and upper thermosphere and electrodynamics in the ionosphere-thermosphere system (e.g., electric field) associated with SSW.
- Modeling studies of interactions between planetary waves, tides, and gravity waves, planetary waves and zonal mean flow, and their effects on the ionosphere; effects of solar variability on the ionosphere-thermosphere response to these dynamical drivers of lower and middle atmospheric origin.
- Observational and modeling studies of the temporal development of the mesospheric and ionospheric response to SSW and recovery from SSW.

---

## *III. Recommendations for 2011 Strategic Capabilities*

As in the case of FSTs, suggestions for Strategic Capabilities were solicited by the SC during the Town Hall at the 2010 Fall AGU Meeting, and by means of multiple announcements through the SPA Newsletter and SolarNews. The number of recommended Strategic Capabilities is significantly smaller than recommended FSTs, in part because proposals for Strategic Capabilities must necessarily identify mature areas that are ready for such investment of resources that will result in deliverables critically needed by the community. Nearly all of the topics recommended below had their genesis in ideas put forward by members of the community. The following is a list of the recommended Strategic Capabilities, divided under the headings of the four Strategic Goals given in Section I. (The order is not prioritized.)

## *IIA. Recommended Strategic Capability for Strategic Goal 1 (Solar Storms)*

### Model of Coronal Mass Ejections

*Capability Description*:

Develop, and make available for community use, a model to investigate CME initiation and evolution in a global background corona.

*Strategic Need*:

Coronal mass ejections (CMEs) are spectacular manifestations of solar activity. They are challenging to study scientifically, and create some of the most important space-weather impacts at Earth. While the mechanism(s) that initiate CMEs are still under debate, a number of candidate mechanisms have emerged and have been studied in numerical models. The environmental context of CMEs (the background corona) strongly influences their observational signatures. We require a capability to explore CME mechanisms in the context of realistic, global coronal fields, and compare the results with a range of remote observations of CMEs and associated phenomena (flares, filament eruptions, post-eruptive arcades, coronal "EIT" waves, dimming regions, white-light observations such as "halo" events, and heliospheric imaging). Ideally, the model will allow the user to select a time period and a location on the Sun (active region or filament that previously erupted) and define a type of CME model. Models that incorporate two or more mechanisms are preferred, to allow researchers to compare the coronal responses between different mechanisms, and could range from the insertion of unstable configurations to slow changes in the boundary conditions that lead to eruption. A set of user-specifiable parameters (e.g., magnetic free energy, shear flow, chirality of filament) should be available to the user for each mechanism. The proposed capability should allow the user to examine the results of the simulated eruption. The results of the model should be useful to a wide range of researchers; not only modelers/theorists but also observers/data analysts attempting to interpret spacecraft data from specific events. Therefore, in addition to providing the model density, temperature, and magnetic fields as a function of time, output diagnostics that can be directly compared with observations should be developed and provided by the model. Preferably the model will also describe the evolution and propagation of the ejecta in the solar wind to 1 AU, and their connection back at the Sun.

*Desirable Features*:

The model would be expected to provide the ability to:

- Select a day or time period for studying an eruption.
- Produce or utilize a realistic global background corona for the time period in question, based on line of sight and/or vector magnetograms or maps.

- Select an active region or other location on the solar surface for the source of the CME.
- Select among different CME initiation models;
- Provide the properties of the CME evolution in a realistic global corona and heliosphere.
- Produce a range of diagnostics that can be directly compared with relevant coronal observations.
- Connect remote and in situ observations.
- Deliverable to CCMC (or other designated center) for runs on demand by community.

*Relationship with previous Strategic Capabilities*:

In 2005, a capability to model the global ambient corona and solar wind for selected time periods was solicited and two groups were selected. In 2006, a capability to model active region magnetic fields was solicited and one group was selected. The new capability solicited here is substantially different, in that the previous capabilities focused on quasi-steady features, prior to any eruption occurring, whereas this capability focuses on the eruption itself and its aftermath.

## *IIB. Recommended Strategic Capability for Strategic Goal 2 (Sun-Climate)*

### Targeted Atomic Physics in Support of EUV & X-Ray Emission Modeling

*Capability Description*:

Extend the current extreme ultraviolet (EUV) and X-ray emission codes by identifying and correcting deficiencies in our understanding of atomic transitions in the EUV and X-ray spectrum. Incorporate the improvements into existing codes (e.g. in CHIANTI, APEC, SRPM, NRLEUV).

The program will consist of four parts:
- Identify and prioritize ions and regions of the solar spectrum that critically require new atomic transition calculations. Priority will depend both on needs generated by current instrumentation and by the need for accurate spectral irradiance codes by the larger LWS community.
- Perform theoretical calculations to establish new or improved line emissivities and wavelengths for ions contributing to these spectral regions.
- Identify transitions and accurate wavelengths in laboratory experiments or observed astrophysical spectra.
- Incorporate the results into existing EUV and X-ray emission codes.

*Strategic Need*:

The solar EUV and X-ray emission is critically important for our understanding of solar variability and its effect on the earth, for a number of reasons:

- Solar EUV radiation is the major energy input to the Earth's upper atmosphere.
- It is highly variable on timescales from seconds to years.
- It provides unique diagnostics of the thermodynamic state of the solar outer atmosphere in the temperature range from $5.5<\mathrm{Log}(\mathrm{Te})<7.0$ and higher.

Because of this, a majority of solar space instruments since Skylab target EUV or X-ray emissions.

Analysis of EUV and X-Ray images and spectra relies heavily on spectroscopic models such as the widely-used CHIANTI and APEC. These models consist of emission codes incorporating atomic databases of energy levels, transition cross sections, ionization equilibria, abundances, etc. They enable the user to predict an intensity spectrum based on a model of the temperature and density of the emitting plasma along the line of sight. These models also provide the basic atomic physics data for spectral irradiance codes such as SRPM and NRLEUV. These spectroscopic models are therefore essential for using new observations to derive quantitative measurements of the physical states of the transition region and corona. They are also vital for efforts to forecast or "nowcast" the EUV and X-ray irradiance spectrum of the sun and to cross-calibrate data taken with different instruments.

Current atomic data still possess substantial inaccuracies that make interpretation of the solar emission in this spectral range extremely difficult, such as those arising from missing levels of high energy configurations that give rise to many, currently missing transitions, and which contribute to enhanced emission of existing transitions through cascading. Discrepancies between the observed and predicted spectra are increasingly realized with the advancement of state-of-the-art instrumentation in solar missions, most currently Hinode and SDO. Updating the atomic databases used by emission codes would therefore substantially improve the power and reach of the data from current and future missions. The improvements will also have a significant impact on comparisons of the full sun spectral irradiance codes and result in improved predictions of irradiance emission.

*Desirable Features*:

This capability would be expected to:

- Identify and prioritize ions and regions of the solar spectrum that critically require new atomic transition calculations.
- Perform theoretical calculations to establish new or improved line emissivities and wavelengths for ions contributing to these spectral regions.
- Identify transitions and accurate wavelengths in laboratory experiments or observed astrophysical spectra.
- Incorporate the results into existing emission codes.

## *IIC. Recommended Strategic Capability for Strategic Goal 3 (Near-Earth Radiation)*

### Multi-Scale Model of the Magnetosphere-Ionosphere System

*Capability Description*:

Develop and make available for community use a global model of the magnetosphere-ionosphere system that can describe the dynamics of plasmas, through a broad range of scales, including kinetic effects.

*Strategic Need*:

Global models of the magnetosphere-ionosphere system, based on resistive magnetohydrodynamics (MHD), have been quite successful in simulating the large-scale aspects of the system dynamics, and are emerging as a practical forecasting tool. As a result of previous investments these models are now available to the space physics community through the CCMC, and they are becoming an essential tool for advancing our physical understanding of this system. However, these models do not include some important physical processes, described below, that we know to be important in the coupled system. Furthermore, in order to be useful as an accurate predictive tool, investments need to be made to create models capable of using state-of-the-art high-performance computing systems.

It is well known that the plasma in the magnetosphere contains multiple ion species and has processes that occur at length scales smaller than those described by classical MHD. This is easily seen at the small scales near shocks or reconnection regions. In reconnection layers Hall MHD and/or fully kinetic models have uncovered new physics absent in classical MHD. Furthermore, microscale studies have shown that the reconnection rate is dramatically altered when a heavy ion species is present in the reconnection region. The effect of these features on the global system driven by solar wind conditions remains a fundamental and unanswered question. In addition, recent work has shown that mass outflow from the ionosphere plays an important role in the formation of the ring current as well as the dynamical evolution of the magnetosphere. Accurately representing the mesoscale features in the magnetosphere is also very important in driving the thermosphere-ionosphere system. These and other physical issues require the development of numerical model of geospace that is capable of resolving or representing the relevant microphysics while preserving the macroscale representation of the system, including the ability to handle multiple species if needed.

Development of this numerical model will require the creation of new computational algorithms and tools to take advantage of the latest developments in computational hardware that will be needed to obtain the resolution desired to resolve the length scales of physical interest. Meeting the physics challenge describe above will not simply be met by more computing cycles, but will require the development and implementation of efficient and stable numerical algorithms.

*Desirable Features*:

- Capability to study processes occurring at ion scales in the global context.
- Capability to handle multiple ion species.
- Capability for electrodyamic and mass coupling to the ionosphere.
- Capability to produce thin current layers and dissipation regions that can be compared with observations.
- Capability to model the system during storms and substorms and make predictions that can be tested with observations from spacecraft.
- Comprehensive validation and verification plan to quantitatively assess model performance against observations throughout geospace.
- Efficient operation on modern computational architectures and scaling to thousands of processors.
- Deliverable to CCMC for community access.

*Relation with Previous Strategic Capabilities*:

In the 2005 solicitation, two Strategic Capabilities focused on developing "A Comprehensive Magnetosphere-Ionosphere Model" where funded. These Strategic Capabilities are now nearing completion and their models have been delivered to the CCMC for community utilization. The main physical model used for magnetospheric dynamics in these models is resistive MHD. This Strategic Capability is clearly differentiated by its focus on using models that extend MHD in significant ways, such as by the inclusion of kinetic effects and multiple species to model the magnetosphere, and by its emphasis on novel algorithms for state-of-the-art computing.

---

## Assimilation of Data in to Physical Models for Realistic Specification of the Inner Magnetosphere

*Capability Description*:

Develop and deliver a global magnetospheric model capable of assimilating comprehensive magnetospheric and ionospheric datasets to reproduce realistic global magnetic and electric fields, and particle distributions of the inner magnetosphere.

*Strategic Need*:

The LWS/TR&T program emphasizes the need to deliver the understanding and modeling required for effective forecasting/specification of inner magnetospheric radiation and plasma. Looking to the meteorological and ionospheric-thermospheric sciences, assimilation of data in to global models has been an integral part of a successful approach to achieve forecasting, or even nowcasting capabilities. Magnetospheric data sets have now become so dense and well-organized, and empirical models so mature that magnetospheric research has ripened for a major transition to combine state-of-the-art first principles global models, comprehensive data sets and empirical models to take that same step towards a predictive capability.

The most outstanding space weather phenomena occur in the inner magnetosphere (L<8). For example, geomagnetic storms and substorms display a severely distorted magnetic field due to the presence of an enhanced ring current, which in turn is also responsible for modifying the large-scale electric field through its ionospheric closure. The plasmasphere is governed by the dynamics of that electric field and its distribution mediates wave activity crucial for the acceleration and loss of the outer electron radiation belts that are also heavily modulated by the structure and dynamics of the geomagnetic field.

Physics models of the inner magnetosphere exist that self-consistently compute the E- and B-fields, and particle distributions to some degree of accuracy, but not to the point where forecasting or now casting capabilities can be claimed. Some empirical models have reached a stage where its use of relatively dense data sets has enabled a specification of the global state of the inner magnetosphere given a set of control parameters. However, their spatial and temporal scales are still on the order of $R_E$ and several hours, which is not sufficient to capture the dynamics. Assimilation of particle data in to inner magnetospheric models is an active area of research with some success by US, European and Japanese teams, some of which are ongoing NASA funded efforts, but several important data sets have not been assimilated and several techniques have not been implemented and tested.

Therefore, a large-scale coordinated effort is required to develop a capability that combines the correct physics of first-principles models and assimilates comprehensive data sets of the magnetosphere and ionosphere to achieve realistic description of the structure and dynamics of the fields and particles of the inner magnetosphere. Such a model, or models, would not only be critical for realistic specification of electric and magnetic fields, and particle distributions, but any aspect of its output would be useful for other models such as radiation-belt models and circulation models of the ionosphere-thermosphere system. More importantly, the model, or models would greatly increase the science return and planning of future missions such as *RBSP* and *MMS*.

*Desirable Features*:

- Capability to assimilate comprehensive data sets of the inner magnetosphere and ionosphere. For example inner magnetospheric E- and B-fields, plasma pressure and the plasma sphere (*IMAGE*, *Cluster, RBSP, AMPTE/CCE, GOES,*

*LANL Geosynchronous*), ionospheric field-aligned currents (*AMPERE*), ionospheric convection (SuperDARN), magnetic fields (superMAG) and electron densities.
- Specification of the global large-scale electric and magnetic fields, and particle distributions at <0.5 $R_E$ and <30 min time resolution.
- Method to validate the output with out-of-sample distributions.
- Ability to take absolute time and driving parameters such as solar wind conditions as input
- Ability to be run on demand from a designated modeling center and to deliver model output in appropriate formats for use by other models.

The deliverables are:

- One, or several models that combines first-principles models of the inner magnetosphere with comprehensive data sets (see example list above) to reproduce realistic large-scale electric and magnetic fields, and particle distributions of the inner magnetosphere.
- Documented techniques of data assimilation and their numerical implementation

*Relation with Previous Strategic Capabilities*:

There is minor overlap with the 2005 Strategic Capability on "A Comprehensive Magnetosphere-Ionosphere Model", but the focus of that effort was not on assimilating comprehensive magnetospheric and ionospheric datasets to reproduce realistic global magnetic and electric fields, or particle distributions of the inner magnetosphere. An earlier version of this Strategic Capability was proposed in 2009 but not selected.

---

## *IID. Recommended Strategic Capability for Strategic Goal 4 (Ionosphere-Thermosphere)*

### Geospace plasma/neutral dynamics model

*Capability Description:*

Develop an interactive model of plasma/neutral dynamics and energetics in the near-Earth space environment driven by atmospheric and solar/solar-wind inputs.

*Strategic Need:*

The near-Earth space environment is strongly coupled through interactions across many different domains: plasma flows in the ionosphere, plasmasphere, and magnetosphere strongly influence the densities and dynamics of these coupled geospace regions; waves from the lower atmosphere influence the ionosphere;

various mechanisms operating in the inner magnetosphere contribute to heating of the plasmasphere and top-side ionosphere; and disturbance electric fields affect the net production and transport of plasma at all latitudes. These processes also produce major perturbations in thermosphere/exosphere densities, temperatures and winds. Finally, simulations and observations show that heavy ions accelerated out of the ionosphere into the magnetosphere can have dramatic influences on the dynamics of the magnetotail.

Models exist for components of this system: thermosphere, exosphere, low- to mid-latitude ionosphere, plasmasphere, polar ionosphere and polar wind, and magnetospheric convection and magnetohydrodynamics. However, often they are not linked in ways that allow analysis of mutual feedbacks among the different components, such as the ways in which magnetospheric electrodynamics, particles, and plasma waves energize and transport plasma in the plasmasphere and ionosphere, or the ways in which plasma outflows from the ionosphere affect magnetospheric dynamics and particle sources and losses from the ring current. Some progress has been made in thermosphere-magnetosphere interaction via feedback from mass, energy and electromagnetic processes. Thus, these topics are ripe for a full-scale modeling effort that will consolidate community understanding of these plasma and neutral processes.

This initiative seeks to develop a coupled model of the geospace plasma that links the thermosphere, ionosphere, exosphere, plasmasphere, and polar ionosphere; that self-consistently models the energetics, chemistry, and electrodynamics of this plasma; that quantifies the conductance linking ionized regions, that simulates outflows into the magnetosphere and the consequences of this outflow on magnetospheric dynamics; that physically represents ionospheric and magnetospheric storm effects; and that provides information relevant to the prediction of thermospheric and ionospheric variability. All modeling efforts have and will be informed by data from NASA spacecraft (ACE, AE, POLAR, CNOFS, FAST, RBSP) along with AMPERE, the future SWARM mission and ground based observations. Empirical components may be used to represent phenomena for which quantitative physical models do not yet exist.

*Desirable Features*:

- Two-way coupling of ionospheric/plasmaspheric/magnetospheric models with a realistic representation of exospheric and thermospheric density, composition, and winds during quiet and disturbed conditions.
- Coupling with models of the lower atmosphere, driving thermospheric dynamics with changing tides and other upward propagating phenomena.
- Self-consistent calculation of global electrodynamics including equatorial electric fields driven by penetration electric fields and the neutral wind dynamo.
- Two-way coupling of ionospheric and plasmaspheric models with models of magnetospheric magnetohydrodynamics and ring-current physics.
- Interhemispheric transport of plasma, such as photoelectrons.

- Exospheric redistribution of light atoms.
- Capability for forward modeling of observable parameters of the ionosphere, thermosphere and plasmasphere for data assimilation.
- Model formulations that allow easy transition from empirical to full-physics and/or data assimilation components.
- Ability to include improved empirical models for benchmark comparisons.

The deliverables are:

- A first-principles, two-way coupled model of the thermosphere, ionosphere, exosphere, and plasmasphere, including calculation of: global ionospheric conductances from magnetospheric and solar input; ionospheric and thermospheric outflow; plasma transport through altitude and across latitude; neutral dynamics of the thermosphere-exosphere; and time-dependent location of the dynamic plasmapause.
- Global time dependent outputs of: self-consistent ionospheric conductances, electric potentials and ion drifts, high-latitude ion outflow; neutral densities, temperatures and winds; exospheric and, plasmaspheric densities and composition.
- Interface module(s) to link model input and output to an external ring current model.
- Climatological outputs for: solstices, equinoxes, solar maximum, and solar minimum.
- Delivery of the model to the CCMC and support of the model through the transition to runs-on-request including validation and metrics results that show improvement of the coupling as more physics is added.

*Relation with Previous Strategic Capabilities*:

In 2005 LWS supported a Comprehensive Magnetosphere-Ionosphere Model strategic capability and in 2008, a strategic capability on Integrated Model of the Atmosphere-Ionosphere System. The former capability included some study of plasmasphere, ionosphere and polar regions, however, little effort on linking with neutral interactions. Rather, there was a strong emphasis on plasma interactions between the inner and outer magnetosphere and on medium and high energy particles in the ring current and radiation belt. The latter capability placed stronger emphasis on lower atmosphere, solar irradiance, galactic particles, anthropogenic effects, along with a focus on chemistry. Neither capability focused on providing self-consistent ionospheric conductances, electric potentials and ion drifts, high-latitude ion outflow; neutral densities, temperatures and winds; exospheric and, plasmaspheric densities and composition. Results from recent focused science studies set the stage for a comprehensive effort in geospace plasma/neutral dynamics modeling which were not addressed in previous strategic capabilities.