Drafts of Revised SSAs:

SSA-I: Origins and Variability of Global Solar Processes
(revised from original SSA-0, Solar Electromagnetic, Energetic Particle, and Plasma Outputs)

SSA-II: Solar Eruptive and Transient Heliospheric Phenomena
(extracted from numerous original SSAs)

SSA-III: Acceleration and Transport of Solar Energetic Particles
(revised from original SSA-3, Solar Energetic Particle Forecasting)

SSA-IV: Variability of the Geomagnetic Environment
(revised from original SSA-1, Geomagnetic Forecasting)

SSA-V: Dynamics of the Global Ionosphere and Plasmasphere
(revised from original SSA-4, TEC Forecasting)

SSA-VI: Localized Ionospheric Irregularities
(revised from original SSA-5, Scintillation Forecasting)

SSA-VII: Composition and Energetics of the Neutral Upper Atmosphere
(revised from original SSA-2, Satellite Drag Forecasting)

SSA-VIII: Radiation and Particle Environment from Near Earth to Deep Space
(revised from original SSA-6, Radiation Environment Forecasting)

SSA-IX: Stellar Impacts on Planetary Habitability
(new topic)

SSA-I: Origins and Variability of Global Solar Processes

Key Elements: Solar Cycle, Dynamo, Irradiance, Solar Wind

Executive Summary

The goal of this SSA is to derive a better understanding, leading to a predictive capability, of the processes that drive the formation, interaction, and emergence of magnetic flux systems from within the solar interior, as well as of those that generate the background particle (solar wind) and radiation (irradiance) outputs of the Sun outside activity events, at all time scales.

Scope

The properties of the solar interior are required as constraints for investigations of the solar magnetism that lie at the heart of our interaction with the sun. Largely masked from direct observation, the flows and feedbacks between the solar magnetic field and large-scale flows within the solar interior drive the persistent modulation of our star's electromagnetic, energetic particle, and plasma output that in turn drives variability throughout the space environment and the upper terrestrial atmosphere. Characterizing the properties of the solar convective interior remains a significant challenge and yet an understanding of these properties is needed in order to predict long term solar inputs to the space environment and Earth's atmosphere. Also, it is necessary to understand the mechanisms that convert magnetic energy into solar wind heating and acceleration, and how they influence solar irradiance at all wavelengths, from the photosphere to the corona, so that adequate forecasting capabilities can be developed.

The "unusual" temporal extension and depth of the 2009 solar minimum in addition to the episodic, but relatively subdued output of Solar Cycle 24, have underlined deficiencies in established theories. These conceptual roadblocks have placed a premium on observational investigations of solar interior structure and understanding large-scale evolutionary patterns visible in the historical data such as the "Torsional Oscillation" and even the "given" patterns of differential rotation, as well as meridional circulation. Furthermore, measurements of solar wind properties have indicated that the wind acceleration, heating and ionization mechanisms were also affected by the depth of the 2009 minimum. The causes of such changes need to be understood and their effects on the background solar wind need to be established.

It is imperative for our community to develop stronger feedbacks between observations (e.g., remote sensing techniques, in situ measurements, etc.) and modeling efforts of the solar interior, solar irradiance and solar wind to place stronger constraints on the long term evolution of the "background" Sun. Enabling development of robust data-assimilation methodologies for forecasting the evolution of the system is needed. Such well-constrained models can then be used to inform modeling and forecast activities across the international community.

This SSA seeks studies that will provide a science-based understanding and forecast capability for the long term (days to decades) variability of solar magnetism, solar irradiance and solar wind. Note that the corresponding short timescale / impulsive events are the focus of SSA-II. In particular, studies encouraged by this SSA are those that focus on a better understanding of the physical processes that drive the formation, interaction, and emergence of magnetic flux systems in the convective solar interior across the timescales relevant to the variability of space climate, as well as studies that focus on the drivers of solar wind and irradiance variability.

Success measures will include the development and application of observationally constrained modeling efforts across the LWS discipline that lead to insights into, and therefore improved forecast capability for, solar-forced electromagnetic, energetic particle, and plasma drivers of the space environment and the Earth's atmospheric inputs across temporal scales from days to decades.

Models

- Observationally testable models of large-scale flows in the solar interior that relate to, and push advances in, observational techniques.
- Models of helioseismic signatures in and around the complex interfaces likely in the convective interior.
- Models of magnetic flux production in a rotating convective plasma with observationally testable outputs.
- Models of magnetic flux system interaction including the formation of complex active regions.
- Models of the variations in solar radiative output due to changing solar atmospheric magnetic field conditions.
- Models of global solar magnetic field and its evolution, especially those that are data assimilative and can be used as drivers of global corona and solar wind models.
- Models of instabilities at the radiative–convective interface, tachocline, their detectability and their potential impacts on magnetic flux emergence and observational tests.
- Models of solar wind heating, acceleration and evolution from the Sun into the heliosphere.

Observations

Interpretation of available datasets from the Solar Dynamics Observatory (SDO), Solar-Terrestrial Relations Observatory (STEREO), Hinode, Global Oscillation Network Group (GONG), Synoptic Optical Long-term Investigations of the Sun (SOLIS), and other space- and ground-based assets including long- term proxies of solar variability (e.g., Be10, and other proxies), in-situ measurements solar wind properties from any available space mission.

Predictive Goals / Connections / Products

- Outputs capable of reproducing the large-scale flow patterns of solar activity and their variability over wide-ranging timescales (up to centuries).
- Models of the decadal to daily solar magnetic activity to be used as drivers for electromagnetic, energetic particle, plasma and eruptive models of the solar system environment.
- Records and proxies of radiative and energetic particle inputs into the terrestrial system.
- Global models that predict the state and evolution of the solar magnetic field.
- Global models that predict the properties of the background solar wind in the entire Heliosphere.
- Models that explain solar wind heating and acceleration, and provide observables to test acceleration mechanisms.

Measures of Success

- All statistical analyses need to address the uncertainty in the estimates of magnetic variability and flow characteristics.
- Demonstration of a capability to estimate timing and magnitude of solar magnetic activity cycles.
- Demonstration of a capability to predict the state of the global solar magnetic flux on a surface (e.g., the photosphere) or within a specific domain (e.g., the corona) of the sun.
- Demonstration of a capability to estimate onset and magnitude of global flux emergence events: start time, end time and maximum amplitude of the event.
- Demonstration of a capability to predict the solar wind properties to be measured by available spacecraft.
- Demonstration of capability to predict the variable radiative output of the solar atmosphere.
- Demonstration of a capability to provide background solar wind plasma properties to models of Coronal Mass Ejection evolution and propagation in the Heliosphere.

Types of Investigation

- Consolidation and conservation of historical synoptic observational records;
- Development of methods to discriminate between the presence of subsurface magnetic fields and thermal structures in the convective interior;
- Determination of the cellular, or multicellular, structure of the plasma flow fields at all depths and latitudes at and below the visible surface of the sun;
- Analyses revealing how the evolution of the flow field and magnetic environment of the solar poles can affect the dynamo and the solar activity cycle;
- Analysis across the gamut of ground- and space-based platforms to exploit ancillary observations of the corona, solar wind, and heliospheric environment and help constrain the global evolution of the magnetized system;
- Development of methods to constrain and inform forecast models of solar activity on year to multi-decadal scales;
- Development of accurate historical records including proxies such as Be10 for solar activity.

SSA-II: Solar Eruptive and Transient Heliospheric Phenomena

Key Elements: Flares, Coronal Mass Ejections, Corotating Interaction Regions

Executive Summary

The goal of this SSA is to 1) understand and forecast the occurrence and evolution of impulsive events, i.e., flares, coronal mass ejections (CMEs), and corotating interaction regions (CIRs), originating either at the sun or in the heliosphere that have negative impacts on assets in space or on the ground, and to 2) understand and forecast their input and propagation through the heliosphere.

Scope

Impulsive events are at the heart of Space Weather, as they constitute the major threat to orbiting satellites, energy infrastructure and communications, and human well-being in space. They are the manifestations of solar magnetism.

Sudden releases of magnetic energy in active region structures, likely due to magnetic reconnection, lie at the heart of *flares*, which heat the plasmas in these active regions to temperatures in excess of ten million degrees Kelvin in a matter of minutes and increase the emission of the most energetic radiation of the host active region by orders of magnitude. Many different processes are thought to be the cause of *coronal mass ejections* (CMEs), by which a large scale magnetic structure -- often including an embedded flux rope -- is accelerated into the heliosphere. At the same time, CME plasmas are non-uniformly heated, although measurements of the relative amounts of energy released in the form of heating or acceleration of material are scarce, and the fraction of released energy poured into the different CME components is not well known. In the heliosphere, streams of fast solar wind may overtake slow wind plasmas and generate compression regions and/or shocks, which accelerate and energize particles in their own right. These stream interaction regions (SIRs) can even persist for a few solar rotations, generating *co-rotating interaction regions* (CIRs). When they reach the Earth, they result in potentially dangerous substorms.

The high-energy electromagnetic radiation coming from flares, as well as the particles and magnetic fields carried by CMEs, CIRs and SIRs provide the greatest hazards to human infrastructure in space and on the ground and to humans in space, including astronauts and flight crews on transcontinental flights. Forecasting the onset, evolution, and properties of these phenomena is the one of the primary goals of Space Weather Science.

This SSA is seeking studies devoted to: 1) the processes responsible for flares, the evolution of active regions prior to flares, and the identification of precursor signs of flare explosions in active regions; 2) the pre-eruption evolution, trigger mechanisms, acceleration, heating and propagation of the magnetic and plasma structures giving rise to CMEs; and 3) the formation and evolution of SIRs and CIRs, and the mechanisms that make them accelerate particles. Studies of the background solar wind solicited in SSA-I feed into this SSA, as the solar wind constitutes the medium through which CMEs travel and influences their geo-effectiveness; in the same way, results from this SSA will feed into SEP studies solicited in SSA-III as SEP particles and their seed population can result from CME and flaring events. This SSA is focused on these eruptive and transient magnetic phenomena themselves.

Models

A large number of models have been developed, which try to account for each of the phenomena that are part of this SSA. These models include models for CMEs, flares, and SIRs and CIRs, and they vary significantly in terms of complexity and scope. Models of CMEs focus on the evolution of active region structures prior to eruption, trying to reproduce the evolution that leads to CME onset under different scenarios. These models then endeavor to predict the evolution of CME plasmas after onset. Flare models aim to capture both the quasi-static evolution of active region plasmas until the conditions for magnetic reconnection are formed, and then predict the evolution of the magnetic field and of the flare plasmas from the photosphere to the corona during the impulsive, peak and decay phase. Current global 3D MHD models are able to predict the formation and the evolution of SIRs and CIRs as part of the solar-wind evolution in the Heliosphere, as well as to account for the interaction of CMEs with the ambient solar wind.
A main limitation in the current suite of models is the lack of reliable and quantitative predictive capabilities of when and where one of these events will take place in the future, given a set of current observations. In addition, predictions of the internal magnetic structure of interplanetary CMEs, in particular the North-South magnetic field component which is a critical driver of Earth's space weather, are still challenging for current models. Furthermore, only a few models are able to predict emission from CME plasmas, and to calculate the charge state evolution of each CME component, so that direct comparison with observations is usually limited to large-scale CME properties.

The ultimate goal of this SSA is the development of models that are capable of: 1) predicting the occurrence and evolution of flares, CMEs and the formation of SIRs and CIRs, as well as their geo-effectiveness and 2) incorporating all of the relevant physics and utilizing as input observations from the Heliophysics observatory. The development of observables to directly link CME properties to specific physical processes is also necessary.

Observations

Remote sensing observations and in-situ measurements are the two tools at our disposal to study solar activity. Flares have been observed at all wavelength ranges from both the ground and space-based remote sensing instruments, despite the difficulty in predicting when and where they will occur. Available flare observations provide a wealth of diagnostic tools to measure the properties of flaring plasmas before, during and after reconnection. However, there remain important limitations in our current flare observing capabilities, such as resolving reconnection location, as well as cadence and field of view (spectrometers) and limited diagnostic capabilities (narrow-band imagers).

CME observations suffer from three additional limitations: first, no observation exists that can follow the same CME plasma observed leaving the Sun by remote sensing instruments until it reaches in-situ instrumentation as an interplanetary CME (ICME). Second, CMEs' large-scale and dynamic nature makes it nearly impossible to follow their early evolution as they rise from the Sun with the necessary spectral, spatial and temporal resolution at the same time. Third, in-situ measurements only capture a minute portion of ICME plasmas, as well as SIRs and CIRs, making it impossible to directly sample the very diverse plasmas that compose them. Still, the combination of remote sensing and in-situ observations can provide us important clues to the physical processes that take place before, during and after a CME erupts.

The availability of long-term, large scale observations of the Sun and of the solar wind has recently led to the rise of groups that utilize machine learning and artificial intelligence to mine the available long-term data sets in search of new methodologies and algorithms to predict the occurrence of flares and CMEs. In turn, a possible future investigation may be that the resulting predictions of event occurrence perhaps can be used to shed light on the physics giving rise to the event itself.

Predictive Goals / Connections / Products

This SSA focuses on advancing our ability to predict the occurrence and evolution of flares, CMEs, SIRs and CIRs with the goal of building the infrastructure that allows for quantitative Space Weather forecasting. Specifically, this SSA is seeking advances in our ability to:

- Predict flares with significant (> 12 hours) lead time from remote sensing observations
- Predict flare-related irradiance variations with significant (> 12 hours) lead time
- Predict the onset of a CME from a pre-existing large scale solar structure
- Predict CME propagation, properties, and arrival time with significant (> 24 hours) lead time

- Predict CIR, SIR development and arrival time with significant (> 24 hours) lead time
- Predict the interplanetary B_z orientation for incoming transient structures

These goals will be best obtained with investigations that utilize modeling and observations from many different types of instruments. Studies addressing this SSA may overlap with studies fundable by other Heliophysics programs (e.g. Supporting Research; Guest Investigator; Theory, Models and Simulations; Strategic Capabilities), but what makes the studies submitted in response to this SSA unique is their focus on developing the knowledge and scientific understanding to improve our Space Weather predictive capabilities. Furthermore, this SSA is seeking studies that address the underlying physics behind all these capabilities, rather than developing operational capabilities which will be addressed by the new Space Weather Science and Applications (SWxSA), as the latter program focuses on transition tools, models, data and knowledge from research to operational environments.

Measures of Success

Successful investigations will result in fundamental progress in our understanding of the processes that determine the buildup, onset and evolution of transient heliospheric events (flares, CMEs, SIRs, CIRs), which will allow us to improve our capability to predict:

- Flare occurrence, hours ahead
- CME occurrence, arrival and geoeffectiveness, hours to days ahead
- CIR, SIR arrival and effectiveness, hours to days ahead
- Northward or southward oriented magnetic field at the Earth (Bz), hours to days ahead
- Transient irradiance variations to the Earth's atmosphere

These capabilities will lead to be able to provide "all clear" predictions.

A critical component of any study will be the assessment and mitigation strategies of the uncertainties associated with the data, the modeling, and the predictions.

Types of Investigations

This SSA needs investigations that couple predictive models of space-weather events with models of the background solar atmosphere and heliosphere, and with observations from a wide array of space and ground-based instruments from the Heliophysics Observatory working at all wavelengths.

Of particular importance is the use of the new ground-based facilities able to measure the coronal magnetic field that will be deployed in the next few years, such as DKIST (high spatial resolution, small field of view) and the upgrade of the CoMP instrument (UCoMP, whole corona), part of the Mauna Loa Solar Observatory. Investigations that make use of machine learning, mining the vast amount of observations accumulated by many spacecraft of the last decades are also welcome.

The investigations pursued under this SSA will involve a combination of two or more of the following topics:

- Machine learning studies;
- Data assimilative, time resolved models;
- Integrated sun-to-Earth models;
- Observational characterization of the properties of flares, CMEs and CIRs at any wavelength/energy range;
- Observational characterization of the input of flares, CMEs and CIRs to the Geospace environment;
- Determination of new diagnostics using in-situ, remote sensing (at all wavelengths), and a combination of in-situ and remote sensing;
- Observations of the coronal magnetic field, either at active region scales, or over the full corona;
- In-situ diagnostics of solar wind, CIR, SIR, ICME properties;
- Integrated remote sensing/in-situ investigations;
- Empirical models of the evolution of solar-wind properties with distance from the sun.

SSA-III: Acceleration and Transport of Solar Energetic Particles

Key Elements: SEP production and propagation, Shocks, Seed Particles, Magnetic connectivity

Executive Summary

Solar Energetic Particle (SEP) events increase radiation hazards throughout the solar system and adversely impact our space- and ground-based assets. Most large SEP events are associated with fast coronal mass ejections (CMEs) in the low corona, typically originating from complex active regions. The prompt response can arrive at Earth in less than an hour from the onset of eruption, followed by the less intense, but longer lasting event associated with the CME shock propagating through the heliosphere. The goals of this SSA are 1) to understand the acceleration and transport of SEPs and related coronal and heliophysics processes, and 2) to build modeling and prediction capabilities for SEP events.

Scope

SEPs are accelerated near the Sun during eruptive solar activities such as flares and CMEs. Large SEP events are of particular importance because they pose severe radiation hazards to humans and assets in space. In these events, high-energy particles are believed to be accelerated by CME-driven shock waves in the corona. There have been a number of factors identified to be important for producing large SEP events. For example, large SEP events observed at Earth are often associated with fast CMEs in the low-corona. Those CMEs are often in the western hemisphere and have a good magnetic connectivity to the Earth. However, not all CMEs that satisfy the two factors lead to large SEP events, suggesting other processes are important as well. Especially, suprathermal ions from preceding events, flares or other sources can be "seed particles" and accelerated by shocks to very high energy. However, the sources and effects of those seed particles are not well understood at all. In addition, SEP observations at Earth's orbit (1 astronomical unit, or AU) usually include a mixture of different physical processes, making it very challenging to pin down the exact role of individual process.

The prediction of these events and their influence on Earth or space assets is a multi-faceted problem. Potentially dangerous active regions must be observed and tracked and the probability of major eruptions needs to be quantified, which makes the SSA reliant on SSA-II. Physical mechanism(s) accelerating the particles should be characterized and modeled within the context of the low solar corona and out into the solar wind, requiring input from SSA-I. SEP transport from the acceleration region(s) to arbitrary points in the heliosphere must be simulated and the uncertainty must be quantified. These transport simulations will rely heavily on magnetic connectivity - both of the background solar wind (SSA-I) and of the dynamic solar wind (SSA-II). Seed particle production and transport need to be observed and modeled and their role need to be determined and quantified.

Models

Models of eruption/shock formation, properties, and propagation in the corona and heliosphere; models of SEP acceleration and propagation from CMEs, flares, and shocks; models providing empirical and/or physics-based predictions of SEP intensity of flares/CMEs; models of seed particle production, transport, and how they influence the high-energy particle acceleration.

More integrated models that couple several processes together will be essential for improving the understanding and prediction capabilities of SEP events.

Observations

Observational characterization of SEPs during large events, especially those factors that can distinguish between competing models; observational characterization of the corona (white-light, EUV and X-ray emission, radio) during large SEP events; Single point and multi-point observations of SEP propagation and distribution; observations of suprathermal particles and their variability; observations of coronal shocks.

In order to achieve significant progress, it will be critical to enhance data-model comparison.

Predictive Goals / Connections / Products

Improve the understanding, characterization, and prediction for large SEP events. Integrated data-driven modeling will be necessary to move towards improved predictive capabilities.

Predictive goals include probabilistic prediction of the intensity of SEP events and increased time periods for all-clear forecasts with higher confidence levels.

Products include predictions of onset, intensity and duration of SEP times, improvement in all-clear forecasts.

This SSA is strongly connected to and reliant upon SSA-I and SSA-II. Particle transport models have to build upon understanding of the background solar wind and turbulence. Particle acceleration models and predictions rely on the onset and evolution of solar eruption events.

Measures of Success

- Demonstration of a capability to quantitatively describe individual SEP events
- Demonstration of agreements between model predictions and observations
- Demonstrate capabilities of predicting and monitoring seed particles and their variability
- Demonstrate capabilities of modeling coronal shocks and magnetic fields and associated particle acceleration and transport
- False alarm rates of large SEP events
- Rate of missed SEP events with high intensity
- SEP intensity predictions of individual events
- Uncertainty quantification of SEP intensity and its evolution

Types of Investigations

Studies of acceleration and propagation of SEPs in realistic fields, CME/flare eruption studies linked to SEP production, studies of the connectivity of SEPs from the Sun to points in the heliosphere, studies of shock formation, evolution, and propagation, studies of suprathermal particle generation, transport, and their roles in large SEP events.

Achieving the goals of this SSA requires both scientific and modeling progress. Progress on this SSA can be made if the following investigations can be supported.

- Mechanisms and observations of SEP acceleration and their comparison, including spectral features and variability of protons, electrons and heavy ions, abundance of minor ions,
- Predict the propagation of SEPs to points in the inner heliosphere, tested by location, timing, and longitudinal separation of SEPs. Even with a forecast of a SEP- producing event on the Sun, an essential question is whether/ when those particles will connect to points of interest in the heliosphere, such as at Earth. This information is crucial for forecasting the onset of prompt events, increasing the time period of all-clear forecasts, quantifying uncertainty and providing higher confidence levels.
- Theoretical and observational studies of seed particle production, variability, propagation, and how they participate in large SEP events.
- Studies of coronal shocks, magnetic geometry, and their effects on SEPs

In addition, breakthroughs could be made by a Strategic Capability (SC) to link together models of CME evolution/propagation, SEP particle acceleration and transport, and realistic models of the corona and solar wind to produce predictions of SEP intensity and duration for real events.

SSA-IV: Variability of the Geomagnetic Environment

Key Elements: Geomagnetically Induced Currents (GIC), Substorms, Geomagnetic storms

Executive Summary

The objective of this SSA is to predict spatial and temporal features of geomagnetic variability in response to internal and external drivers. This goal includes both short and long-term magnetospheric variability and reconfiguration associated with magnetic substorms, storms, and the resulting geomagnetically induced currents.

Scope

Characterizing the spatial and temporal variability of the geomagnetic field remains a significant challenge and is needed to understand the dynamics of the Earth's space environment and its interface with the Earth and lower atmosphere. During periods of strong or dynamic solar wind driving, geomagnetic disturbances, storms, and substorms frequently occur. During these events the dynamics, shape, and topology of the magnetosphere can change in response to varying pressures and local current systems. These changes to the system can impact the Earth's space environment through a number of paths including modifying particles to either feed or deplete the Earth's ring current and radiation belts and generating strong current systems with potentially serious impacts on the planet's surface.

A result of geomagnetic storms and substorms is variability in magnetic fields, or dB/dt, which induce a geoelectric field on the surface of the Earth. The geoelectric field that is strongly dependent on, for example, local ground conductivity conditions drives geomagnetically induced currents (GIC) that can flow in power grids, pipelines and railway systems. Large dB/dt can also negatively impact geophysical exploration surveys.

One of the key, yet insufficiently understood, issues of the GIC topic is how large regional dB/dt or GIC events can get during storm conditions. While moderate events can also have an impact, for example, via premature aging of transformers, GICs during extreme storms conditions are of major interest. Quantification of extreme GIC characteristics is the fundamental quantity that will feed into engineering analyses that will ultimately determine how vulnerable, for example, power grids are to space weather events. Assessments of resilience cannot be carried out satisfactorily without the "extreme boundary conditions" provided by the space physics community.

We are seeking studies that will improve the characterization and prediction of geomagnetic storms, substorms, and extreme GIC events. We are especially encouraging studies that will both quantify statistical occurrence and spatio- temporal characteristics of extreme GIC events and improve our capability to predict extreme GIC events. These activities also include possible studies of the theoretical maximum GIC that will provide a robust, upper boundary that can be used in engineering analysis. Further, it is important that studies will address the local or regional aspect of dB/dt.

Models

The models that this SSA needs to be developed include those that can aid in:

- Long lead-time prediction. This will require models of the external driving parameters of the magnetosphere-ionosphere system, including solar wind parameters, structures, and outputs from SSA-II such as CMEs and CIRs.
- Short lead-time predictions. This will require data-driven models for the magnetosphere, ionosphere, and upper atmosphere and models for geomagnetic induction. Ultimately a systems approach coupling these different domains will be required.
- Statistical models quantifying occurrence, spatial distribution and temporal evolution of extreme GIC events.

Observations

The measurements required to make long lead and short lead time predictions include:

- Solar wind plasma and magnetic field conditions at 1 AU. This includes the products and focused observations from SSA-II.
- The state of the geomagnetic field and electric current systems in the magnetosphere and ionosphere through space and ground-based measurements.
- Ground magnetic field perturbations.
- Accurate maps of the Earth's conductivity profile.

Predictive Goals / Connections / Products

The SSA seeks to improve the ability to predict the state and dynamics of the geomagnetic field and GIC. Specific predictive goals and products include:

- The ability to predict the state of the geomagnetic field (including substorms and geomagnetic storms) as a function of the external and internal driving
- Short lead-time (15-30 min) predictions of extreme GIC events

- Long lead-time (1-3 days) predictions of extreme GIC events
- Solar wind plasma and magnetic field conditions at 1 AU. This includes the products and focused observations from SSA-I and SSA-II.
- Extreme GIC event scenarios providing information about occurrence, variability, spatial distribution and temporal evolution of GIC.

Measures of Success

- All statistical analyses need to also address the uncertainty in the estimates.
- Capability to predict dynamics of geomagnetic storms including start, end, variability, and maximum amplitude of the event.
- Capability to predict dynamics of substorms including start, end, variability, location, and maximum amplitude of the event.
- Capability to capture GIC events: start time, end time, variability, and maximum amplitude of the event. Prediction time windows will vary from days to minutes.
- Capability to capture the predictability of events. Predictability can be characterized using metrics such as forecast contingency tables (of hits, misses, false alarms and correct nulls), probability of detection and probability of false detection.

Types of Investigations

Types of appropriate investigations include theoretical modeling of key solar and space physical processes, analysis through machine learning techniques, data analyses and comprehensive statistical analyses of the state and dynamics of the geomagnetic field and plasma populations within the magnetosphere and ionosphere. Experimental work could be based on ground-based auroral or magnetic field measurements as well as space-based measurements of the field and plasma dynamics in the magnetosphere, ionosphere, and solar wind.

Substantial progress on this Strategic Science Area is possible with the following types of investigations that can be supported:

- Studies of how solar wind structures energetically couple into the magnetosphere-ionosphere system.
- Studies of substorm initiation and dynamics
- Studies of geomagnetic storm dynamics
- Statistical extreme value studies of GIC amplitudes, spatial distribution and temporal evolution.
- Studies of electric current dynamics in the solar wind-magnetosphere-ionosphere system.

- Studies of maximum theoretical rate of change of magnetosphere-ionosphere electric current system.

SSA-V: Dynamics of the Global Ionosphere and Plasmasphere

Key Elements: Electron Density Profile, Total Electron Content, Storm Time Dynamics, Traveling Ionospheric Disturbances, Plasmasphere Refilling

Executive Summary

The goal of this SSA is to understand and forecast the global state of the ionosphere. Specifically, the goal is to determine the total electron content (TEC) and the plasma density profile, which includes information about the electron and ion density and the electron and ion temperature as a function of altitude. The plasma density profile is determined by both space weather and terrestrial weather phenomena. The state of the ionosphere impacts ground-based radio communications and navigation and timing from the surface through low-Earth orbit.

Scope

Understanding and forecasting the plasma density profile requires knowledge of the coupled geospace system: from the ground through space. This includes the neutral atmosphere, the ionosphere, the plasmasphere, the magnetosphere, the solar wind, and conditions on the Sun. Limitations remain in our understanding of the different mechanisms that affect the full vertical extent of the ionosphere and plasmasphere. This directly impacts our ability to model these different regimes during both quiet and storm-time conditions. The goal is to support prediction of the plasma profile globally with a lead time of at least one hour (based on availability of real-time solar wind/IMF measurements), as well as longer-term predictions for up to three days based on solar wind forecasts, and other data where appropriate. A secondary goal is to predict the TEC, an ionospheric parameter commonly utilized by many operational services, with the same lead times.

The contribution to ionospheric variability by processes originating in the lower atmosphere has been increasingly appreciated in both observational and numerical studies, particularly during the last extended solar minimum. Statistical analyses suggest that lower atmospheric forcing can contribute up to one third of the observed ionospheric variability. This forcing is driven by upwardly propagating waves that include tides, planetary waves and gravity waves. Tidal variability is associated with a variety of phenomena such as El-Nino southern oscillation (ENSO), the quasi-biennial oscillation (QBO), the semiannual oscillation (SAO), and sudden stratospheric warmings (SSWs) and thus can impress variability associated with these phenomena on the ionosphere. Planetary waves interact with tides and modulate their impact on the ionosphere. Gravity waves, with their higher phase speeds, directly perturb the ionosphere creating disturbances (i.e., traveling ionospheric disturbances, TIDs) and may seed ionospheric irregularities. Gravity waves are either poorly resolved or not resolved at all in current models, and their parameterization is a major source of model bias. Resolving the relative importance of changes in the wind-driven electrodynamics, changes in conductance, changes in neutral dynamics, and direct forcing by waves to the ionospheric variability is critical to understanding the coupling between the ionosphere and these processes.

In order to move toward physics-based plasma density profile forecasts with quantified uncertainty, improved global models of the ionospheric topside and plasmasphere electron density are needed, to augment more mature models of the bottom side ionosphere. Models of the topside ionosphere, which can be responsible for more than half of the TEC encountered by GPS signals traversing from satellites to ground, must include reliable quantification of proton sources and sinks, which depend in turn on H, O, and O+ densities, with additional accuracy gained by inclusion of He and He+ concentrations. Understanding of the coupling between the ionosphere and plasmashere requires: 1) understanding of the densities and composition of ion and neutral species and how they vary during geomagnetic storms; 2) neutral wind and temperature fields and how they vary, electrodynamics due to dynamo and magnetospheric electric fields mapped to high altitude (above ~300 km); and 3) plasmaspheric erosion and recovery during and following storm periods.

Models

- Models that represent mesoscale processes and reproduce nonlinear interactions between waves and waves and the mean flow.
- Global models of the ionospheric topside and plasmasphere electron density
- Models that include quantification of proton sources and sinks, which depend in turn on H, O, and O+ densities, with accuracy gained by inclusion of He and He+ concentrations.
- Assimilative models with associated inverse theory that constrain the state of the whole atmosphere

Observations

- Neutral wind, temperature, and emission measurements that resolve chemical and dynamical influences on storm-time responses.
- UV and optical airglow emission data acquired from satellite and ground-based photometer networks, of the ionosphere and plasmasphere.
- Solar radiation EUV to X-ray fluxes.
- [O] and [N2] profiles and abundances.
- Ion motions
- Infrared emissions to constrain energy deposition into the top- side during storms.

- Electric fields and plasma convection.
- Magnetospheric energetic neutral atom fluxes.
- TEC derived from Global Navigation Satellite Systems (GNSS), DORIS and other active radio sources

Predictive Goals / Connections/ Products

This SSA seeks to improve the ability to predict the state and dynamics of the global ionosphere. Specific predictive goals and products include:

- The ability to predict the state of the plasma density profile, including TEC, during geomagnetic storms.
- The ability to predict the state of the plasma density profile during episodic meteorological events/episodes such as SSWs.
- Quantifying the role of mesoscale processes on the ionosphere.
- Production of realistic ionospheric irregularities from waves.
- Framework for prediction of plasma density profile in response to different levels and types of disturbance.

Measures of Success

- All statistical analyses need to address uncertainty in their estimates.
- Capability to predict the dynamics of the ionosphere and plasmasphere during geomagnetic storms and substorms.
- Capability of capturing the dynamics of the ionosphere and plasmasphere during meteorological events.
- Capability of capturing the dynamics of the ionosphere and plasmasphere during meteorological events and geomagnetic storms and substorms.
- Capability to characterize impact on infrastructure of ionospheric variability.

Types of Investigations

Investigations that employ observations, empirical modeling (numerical, physics-based model development) and assimilative and data-fusion techniques. Investigations that introduce missing physics in the models, extension of spatial or temporal resolution limits to capture phenomena, and observations that allow definition of boundary conditions for the modeled domains.

- Studies of the response of the densities and composition of ion and neutral species to geomagnetic storms.
- Studies of waves and tides, their generation, propagation, interaction and dissipation.
- Studies of mesoscale processes, their generation, propagation, interaction and dissipation.

- Studies of ion-neutral coupling.
- Studies of electrodynamics due to dynamo and magnetospheric electric fields mapped to high altitude (above ~300 km).
- Studies of plasmaspheric erosion and recovery during and following storm periods.

SSA-VI: Localized Ionospheric Irregularities

Key Elements: Plasma Instabilities, Radio Wave Propagation, Scintillation, Polar Cap Absorption

Executive Summary

This SSA aims to elucidate the complete set of physical mechanisms and plasma instabilities responsible for producing ionospheric irregularities, the causal chains that generate or suppress them, and a full description of how the irregularities interact with radio waves, leading to scintillation or signal absorption. Radio scintillations rank among the most chronic hazardous manifestations of space weather. Scintillation can occur when radio signals traverse or scatter from plasma density variations in the ionosphere. Key focal points of this SSA will be in: 1) understanding the formation, evolution, and dissipation of irregularity structuring; 2) ascertaining how radio signals are degraded by ionospheric irregularities; 3) predicting scintillation, equatorial spread F, and polar cap absorption; and 4) mitigating the effects of ionospheric irregularities on radio communication and navigation.

Scope

Electromagnetic wave propagation at a boundary between two media is governed by refraction, diffraction, and reflection. In the ionosphere, plasma density variations, referred to as "irregularities," can be significant enough to diffract or differentially refract very high frequency (VHF) signals used for communications and trans-ionospheric L-band signals used by Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS). Rapid fluctuations in the received signal amplitude and phase are ionospheric scintillation. Moreover, spatial variations in plasma density can lead to spatially heterogeneous absorption (rather than reflection) of ground-transmitted HF signals.

Localized ionospheric irregularities have scale sizes significant for a given frequency (e.g., a few 100 m for GHz signals). The distances over which the structuring takes place are regional rather than global (e.g., anywhere from tens of km to several-degree bands of latitude and local time). Irregularities are widespread and may occur at low, middle, and high latitude in the E and F regions of the ionosphere.

In some cases localized ionospheric irregularities are associated with larger scale disturbances or phenomena. In the auroral zone, scintillations are strongest during geomagnetically active periods during which particle precipitation can contribute to spatially and temporally varying density, but occur at all times in auroral bands. In the polar cap, scintillations may be associated with 100s of km scale patches of enhanced density; radio absorption may occur in the polar cap with energetic particle precipitation in the D layer. At low latitudes scintillations are associated with local evening equatorial spread F events, which can occur in geomagnetically active and quiet periods. At mid-latitudes scintillation is rare, but possible. With the increasing use of satellite-to-satellite radio signals (e.g., GNSS radio occultations), scintillations may also be caused by irregularity and raypath geometries different than typical satellite-to-ground links.

In many cases, regions of ionospheric irregularities are caused by plasma instabilities and plasma turbulence. For example, equatorially, spread F and L-band scintillations are considered to be triggered by the Rayleigh-Taylor instability. At high latitudes gradient drift, Kelvin-Helmholtz, and current convective instabilities are attributed scintillation-inducing irregularities. The resulting energy cascade and turbulence arising from these instabilities produces localized ionospheric irregularities at a spectrum of scale sizes.

While irregularities have definite climatologies, forecasting them has proven to be challenging, both because the most important ionospheric drivers can be difficult to measure and/or predict and because the ionospheric response to the drivers is often complicated and not obviously deterministic.

This topic focuses on spatial plasma variations that may be treated as turbulent or stochastic phenomena, and their interaction and effects on radiowave propagation. This SSA aims to increase our understanding of the formation, evolution, and dissipation of irregularity structuring; to better ascertain how radio signals are degraded by ionospheric irregularities; to predict scintillation, equatorial spread F, and polar cap absorption occurrence; and to mitigate the effects of ionospheric irregularities on radio communication and navigation. This last area is relevant because, just as measurement of ionospheric refraction of GNSS signals with GNSS receivers has become standard and widespread through the use of multi-frequency receivers, it is anticipated that developing methods for maintaining signal lock when scintillations occur can yield radio signals that are then incisive diagnostics of ionospheric irregularities.

Models

Understanding ionospheric scintillations caused by localized irregularities requires an improved theoretical understanding of the plasma instabilities underlying them. Forecasts incorporating assimilated data will remain ineffective so long as their theoretical foundations (i.e., the prior information known about the process) are incomplete. It is unclear, for example, whether the main sources of free energy and physical processes at work have been correctly identified in all cases, and both the seasonal and day-to-day variability of irregularities are not well accounted for by existing theory as a result. Managing scintillations also requires an improved understanding and modeling of radio wave propagation and scintillation and the different ways that signals are degraded by different classes of irregularities. This is particularly relevant for satellite-to-ground links as well as satellite-to-satellite geometries. For absorption events, radio propagation models are an area of interest. These types of models will aid in developing strategies for minimizing the effects of scintillations on operational communications and navigation systems. Ultimately, irregularity forecast models and scintillation forecast models continue to be highly desired. Forecast models of interest may be physics-based, empirical, data assimilative, or leverage machine-learning algorithms; all are encouraged as long as testing, validation, and quantification of their forecasting ability, "skill score," uncertainties, and probabilities of missed detection or false alarm are addressed rigorously.

Observations

Observations include experimental studies of plasma waves and instabilities aimed at establishing their gross morphology, revealing causal relationships to background driving parameters and geophysical conditions, and fully specifying their climatology. Observations from TIMED, C/NOFS, and FORMOSAT-3/ COSMIC will be leveraged to elucidate the salient processes responsible for scintillations and advance understanding. The DORIS radio measurement system of satellite-to-ground links is available from several non-NASA satellites. Furthermore, ground-based networks of GNSS receivers provide a valuable diagnostic tool for investigating scintillation effects and enable innovative observation schemes such as diffraction tomography. Ground-based radar observations are also valuable. Radio signal information from a number of measurement sources may be folded back into irregularity analysis, modeling, and forecasting.

Predictive Goals / Connections / Products

Solicitations should include FST and SC investigations that lead to improved understanding or predictive capability of irregularities and resulting radio propagation degradations, guided by clearly defined requirements articulated through interaction with the user community.

One goal of this SSA will be to elucidate completely the physical mechanisms responsible for producing ionospheric irregularities. Another goal is to ascertain more completely how radio signals are degraded by ionospheric irregularities, and to use this insight to develop methods for maintaining signal lock when scintillations occur. A third goal of this SSA is the exploration of the means of folding radio signal information back into irregularity analysis, modeling, and forecasting. A final goal is to develop strategies for predicting scintillation occurrence, which is a topic that would align with the NASA Space Weather Science and Applications (SWxSA) program mission. This SSA, in emphasizing the science causing frequent, persistent, and

pervasive space weather, is complementary to the National Space Weather Strategy and Action Plan.
Products include analytical and empirical models that will reproduce unfolding irregularity climatologies through numerical modeling and simulation. Products also include the development of increasingly robust radio signal decoding schemes able to maintain data integrity and signal lock when scintillations or absorption events occur. Forecasts should aim to predict the day-to-day variability in irregularity occurrence, quantifying uncertainty and skill. Forecasts may aim for local or global specificity.

Measures of Success

Physics-based instability and turbulence modeling will provide the onset times, growth times, scale sizes, propagation characteristics, and general morphologies of irregularities consistent with individual observations. Radio propagation modeling should also quantify performance through comparison with observations.

Data-driven or forecast models will establish quantitative benchmarks (skill scores) for success. Metrics should be developed based on specific impact domain requirements. Assessment should go beyond case studies and model runs and should establish rigorous statistical quantification of limits of predictability and demonstrate improved prediction capability resulting from the proposed innovations. Forecast methods should ideally surpass the accuracy of existing forecast methods that are based on climatology and persistence alone.

Types of Investigations

The research would involve theoretical analysis, numerical modeling and simulation, measurement and signal processing, and algorithm design, development, and testing. Past FSTs include “Low-To Mid-Latitude Ionospheric Irregularities and Turbulence” (NNH10ZDA001N) and “Determine the sources of daily variability in the thermosphere and ionosphere” (NNH07ZDA001N). Past LWS Institutes include “TEC and ionospheric scintillation for GPS applications” (2018). Future types of investigations that identify missing physics, use new NASA satellite missions, leverage interest in data science and analytics, prepare the way for forecasting irregularities and their probability of degrading radio signals, and improve performance of radio communications and navigation will be welcome for ultimately helping improve safety and quality of life. Examples of technological systems using radio signals that interact with the ionosphere presently include GNSS-based timing or aircraft landing systems, and in future may include autonomous vehicles, such as small-satellite constellations or autonomous delivery vehicles. Localized ionospheric irregularities have the potential to impact such systems and, therefore, merit sustained scientific study.

SSA-VII: Composition and Energetics of the Upper Neutral Atmosphere

Key Elements: Atmospheric Drag, Heating and Cooling, Waves and Tides

Executive Summary

Earth's upper atmosphere (and ionosphere) is a complex laboratory for investigating radiative processes, plasma-neutral interactions, and wave generation and propagation in the presence of a magnetic field that couples multiple geospace regions above and below. The density distribution of the upper atmosphere, which varies temporally and spatially, is directly responsible for satellite drag. Atmospheric composition controls the make-up of ions that feed the magnetosphere through a combination of refilling, upwelling, and outflow processes. The purpose of this SSA is to reveal, understand, and model the physical processes in the neutral upper atmosphere and to understand its modulation in the coupled magnetosphere, ionosphere and atmosphere system.

Scope

With an increasing number of satellites in low Earth orbit as well as an increasing amount of debris, there is a serious and growing risk of collisions and damage to all satellites, including scientific research satellites and manned NASA missions. Close monitoring of the orbits of every object in space is needed in order to alert operators to the risk of collisions and to address national security concerns.

Low-altitude satellites move within the regions of the upper atmosphere, the thermosphere and exosphere. Their orbits are perturbed by changes in the neutral atomic density resulting from variable solar and auroral activity. Specifically during large geomagnetic storms these perturbations make it difficult to track and predict the locations of satellites, therefore also making it more difficult to avoid collisions with space debris. A long-standing goal of LWS science is to produce improved predictions of the thermosphere neutral density structure and dynamics that will enable more accurate satellite drag and orbit calculations. A number of scientific problems need to be solved in order to achieve a fuller understanding of the variability in the thermosphere, leading to the capability for prediction on timescales of hours to days. The topics to be investigated include:

- Lower thermosphere coupling with adjacent regions above and below.
- The rapid, global response of the thermosphere to sudden enhancements in polar and auroral heating.
- Modes of propagation of these disturbances, from high latitudes to the equator.

- Variability in the cooling rates, due to the effects of nitric oxide, particularly after large heating events.
- Mechanisms of nitric oxide production and how it affects regional densities.
- The thermospheric response to variable solar radiation on short to long timescales, ranging from the timescales of X-ray flares up to those of active region evolution and solar rotation.
- The thermospheric response to variable solar particle fluxes on short to long timescales, ranging from the timescales of solar particle events up to those of high-speed streams and geomagnetic storms.
- Variations in the geocorona, at higher altitudes beyond the exospheric boundary.
- Changes in the composition and temperature of the neutrals in the thermosphere.

The goal is to enable specification of the global neutral density (and temperatures) in the thermosphere and its variations over time by providing the capability to predict the densities that satellites in low Earth orbit will encounter. This specification should be provided with a lead time of at least one hour, although longer-term predictions (up to a week) are desired. Uncertainties should be specified for different environment conditions.

Models

The types of models that could contribute to this solution could include:

- Theories or models for propagation modes, variable cooling rates due to nitric oxide production, atmospheric effects, winds, and tides.
- Numerical or empirical models of atmospheric density and temperature, separate or in combination, having good temporal and spatial resolution and capturing localized structures and dynamics, including the rapid temporal changes following sudden and intense auroral heating, and the subsequent cooling.
- Improved understanding and/or models of composition (and/or temperatures) above the thermosphere.

Observations

Observations that could be used in this project may include, but are not limited to:

- Solar wind velocity and interplanetary magnetic field (IMF).
- Neutral density and composition, or neutral wind measurements from CHAMP, GRACE, and future SWARM or CubeSats.
- Indices or spectra of solar radiation, solar particles, and/or the state of the geomagnetic field.
- Electric and magnetic fields in the ionosphere.

- Remotely sensed observations of the upper atmosphere and geocorona.

Predictive Goal /connections/products

The goal is to derive a model, or coupled set of models, to specify the global neutral density and composition in the thermosphere and its variations over time. These models would be able to feed into precise orbit determination programs. The goal is to predict the densities that satellites in low Earth orbit will encounter with a lead-time of at least one hour along with longer-term predictions out to three days and preferably to seven days. There should be quantifiable levels of uncertainty that are specified for different environment conditions.

Measures of Success

The expected product is a model or a system of thermosphere neutral density and composition specification and prediction models from the current epoch, through 1 hour to at least 3 days, and potentially up to 7 days. Potential users of these capabilities might include U.S. Air Force satellite and debris tracking systems as well as other US military users, NASA conjunction risk management, and private-sector forecasters who aid commercial space operators.

Metrics should be based on specified or predicted neutral densities compared to those measured by CHAMP and GRACE or other high precision density sensors such as SWARM. The USAF HASDM database also provides global, time-resolved mass densities of high accuracy that can be used to assess the validity of a thermospheric density prediction capability. A successful project will make neutral mass density and composition predictions that are demonstrably better than the baseline existing models such as JB2008 or NRLMSISE-00.

Testing with precise orbit determination programs on selected calibration satellites would be a useful way to determine the success or improvement of new atmospheric models. This could be done at the CCMC.

Types of Investigations

The expected types of investigations could include observation-based studies and empirical / machine learning modeling, numerical / physics-based models, or a combination of all three, such as numerical models linked with empirical components and/or data assimilation.

Investigations that use first-principle or numerical models are needed to understand the coupling between different atmospheric regions. Input of energy in the auroral regions could be derived from magnetospheric models or from empirical models. Numerical models may meet the objectives for obtaining a predictive capability.

Investigations that use data analysis or empirical modeling will be needed to serve as a benchmark or validation of numerical models. Such investigations may also meet the objective for obtaining a predictive capability. Assimilation techniques may be useful, as may be optical observations of the upper atmosphere and geocorona.

An investigations of solar radiation at multiple wavelengths and of solar energetic particles and their influence on the upper atmosphere and thermosphere will be required. These energy sources are the primary external drivers of the thermosphere temperature variations upon which the more rapid auroral influences are superimposed. This investigation includes a need to determine how to successfully incorporate solar observations and indices. A long-term (three days or more) predictive capability to predict the effect of solar flares is highly desired, including the effects of sunspot regions on the far side of the sun. It is possible that this investigation will also require optical observations of the upper atmosphere and geocorona, in addition to measurements of neutral densities in the thermosphere.

An investigation into orbital dynamics using an improved description of upper atmosphere structure and dynamics could help reach the goal of an improved capability to predict satellite tracks. This investigation would need to develop an understanding of the processes that may influence satellite drag coefficients, and an understanding of how to derive better values of the drag for realistic satellite geometries.

SSA-VIII: Radiation and Particle Environment from Near Earth to Deep Space

Key Elements: Radiation Damage, Human Exposure, Spacecraft Charging, Radiation Belts, Plasma Sheet, Heliospheric Energetic Particles

Executive Summary

The goal of this SSA is to develop science-based predictions of the dynamic radiation environment and spacecraft-charging environment from the troposphere through Geostationary Earth Orbit (GEO) and out into interplanetary space along with predictions of their relevance to hazardous upper atmosphere and space flight conditions. Research should be carried out to forward the goal of predicting the radiation environment's variability due to Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP) coupling with the Earth's magnetosphere–ionosphere–thermosphere (M-I-T) system as well as propagation within the Interplanetary Magnetic Fields (IMF) and planetary magnetospheres. Research should be carried out to further the goal of predicting the solar-wind-controlled radiation and charging environment in the Earth's magnetosphere.

Scope

The radiation environment from the troposphere to the extended heliosphere is variable, changing dynamically due to GCR and SEP heavy ion, neutron, proton, beta particle, gamma-ray, and X-ray inputs to the Earth's radiation belts. In addition, and of particular relevance to human tissue as well as avionics / space flight radiation dose and dose rate risks, secondary and tertiary particles from high-energy neutron and ion impacts can vary with changes of target atoms and molecules, such as in the tropospheric air mass. The GCR background is typically variable only on the timescale of days, with a long-term trend, which changes slowly, modulated by the effects of the solar Interplanetary Magnetic Field (IMF) that varies with the approximate 11-year solar cycle. The SEP environment, however, can be highly time variable, with impulsive order-of-magnitude changes that can occur in a matter of seconds to minutes in association with solar eruptive events. The Earth's radiation belts are also time varying, particularly the outer electron belt. Intensification of the radiation belts is associated with solar-wind high-speed streams and interplanetary shocks. The GCRs, SEPs, and radiation belts produce an ionizing radiation environment throughout these different regions across a wide range of timescales.

Observations and modeling developments have permitted substantial progress in understanding the drivers and responses of the near-Earth radiation environment. Global radiation climatology specifications have been successfully developed over the past several years. Examples include: the Civil Aerospace Medical Institute (CAMI) model; the Nowcast of Atmospheric Ionizing Radiation System (NAIRAS); the Automated Radiation Measurements for Aviation Safety (ARMAS) aviation altitude dose rate measurements; the Rad-X high-altitude balloon flights; the energetic particle measurements throughout Earth's radiation belts on the Van Allen Probes mission; and even the boundary condition specification of the radiation environment measured by the Lunar Reconnaissance Orbiter (LRO)/CRaTER instrument at the Moon and by the Advanced Composition Explorer (ACE) mission at L_1. However, the variability and forecasting potential of the coupled systems behind this radiation environment are not yet well quantified, particularly on short time scales on the order of minutes to hours.

As national and international entities are actively investing resources into promoting human-rated, prolonged interplanetary space flight, the Living with a Star (LWS) Program should provide a pathway for key research and application-development opportunities that would contribute to safe human travel through interplanetary space. There is an increasing need to develop a cohesive understanding and awareness of the dynamic solar radiation environment throughout the heliosphere as it relates to the risks posed to biological tissue and critical spaceflight hardware. Targeted research can lead to predictive and mitigation strategies en route (e.g., flare impact on biological tissue & hardware, lead times, routine data products needed, modeling of the astronaut/spacecraft environment, recommendations for reducing risk and impact). Building this capability will necessitate cross-disciplinary research, combining knowledge from the fields of space medicine and heliospheric physics. First principles and empirically based models, combined with new data streams are needed to permit substantial progress toward predictability.

Increasing reliance on space-based hardware calls for increased accuracy in predicting the Earth's radiation and charging environments. The measurements of Van Allen Probes and the science it has stimulated have led to substantial recent progress in the understanding of the radiation belts, however there are still outstanding scientific questions about the coupling of the plasmas of the magnetosphere to the radiation belts. The spacecraft-charging environment has been less studied and first-principles understanding and models of the driving of this environment are needed.

Models

First principles, empirical, and data assimilative models for basic science component areas are needed for improving predictive capabilities of the radiation environment at aircraft, Low Earth Orbit (LEO) spacecraft, Geostationary Earth Orbit (GEO) spacecraft altitudes, Van Allen radiation belts, interplanetary space, and planetary magnetospheres; first principles, empirical, and data assimilative models for basic science component areas are needed for improving predictive capabilities of the charging environment.

Observations

Primary and secondary particle fluxes from GCRs and SEPs, possibly including more neutron monitor observations at a variety of magnetic latitudes as well as heavy ions in deep space, energy spectra and particle Linear Energy Transfer (LET) at altitudes from the Earth's surface out to the system boundaries in deep space, through to deep space, and calibrated dose/dose rate measurements at all layers for model validation. High-quality multi-spacecraft measurements of the radiation belt fluxes and of upstream solar-wind conditions exist going back decades. Radiation-belt measurements (like Van Allen Probes) that include measurements of the hot and cold plasmas and of plasma waves are needed. There are existing data sets of spacecraft measurements of the hot-electron fluxes in the Earth's magnetosphere simultaneous with upstream solar-wind measurements.

Predictive Goals / Connections / Products

Improve the understanding, specification, and prediction of the radiation environment from the troposphere to interplanetary space, and within planetary magnetospheres – particularly for high radiation disturbed periods such as during solar proton events and during geomagnetic storms. Improve specification and prediction of the charging environment in the Earth's plasma sheet and auroral zone.

This Strategic Science Area (SSA) is strongly connected to, integrated with, and reliant upon all of the other LWS program SSAs and necessitates cross-disciplinary research, combining knowledge from the fields of space medicine and heliospheric physics. In particular, the SSA is closely connected to SSA-III on SEPs. This SSA is very strongly connected to the NASA Space Weather Program and to the needs of agencies such as NOAA, the Department of Defense, and the Department of Energy.

Example products include:

- New data sets of primary and secondary particles along with dose and dose-rate data ~~sets~~;
- Improved specifications and a new prediction capability, especially using data assimilation, for the radiation environment's effective dose and dose rates based on GCR,

SEP, and radiation-belt fluxes, cutoff rigidity, atmosphere density, and gamma-ray/X-ray inputs;

- M-I-T coupling as it affects high-energy particle precipitation, radiation environment (near-Earth, interplanetary, and planetary magnetospheres);
- A capability that may lead to alerts for operational users of the impacts of extreme radiation conditions in their environment.
- A scientific understanding that would lead to a capability to predict the spacecraft-charging environment in the Earth's magnetosphere based on upstream solar wind conditions.
- The coupling of existing models with a data assimilative approach for current-epoch specification and near term prediction would represent a major advance in the community.

These outputs should be relevant to such potential users as commercial aviation crew, frequent flyers, and pregnant mothers; high altitude private and military jet crew and passengers; space tourists, astronauts en route to and at locations external to Earth, and critical protective space flight systems; aircraft and spacecraft hardware.

Measures of Success

Validation and verification, including metrics, of new specification and prediction capabilities that can be compared with current state-of-art practices; accountability for providing the investigation's results to defined users, to the scientific community, and to the public at large.

Types of Investigations

Substantial progress on this Strategic Science Area is possible with the following types of investigations that can be supported:

- New observations and characterization of primary and secondary particle GCR and SEP radiation sources (heavy ions, neutrons, protons, beta particles, gamma-rays, and X-rays) using *in situ* and/or remotely sensed measurements from ground, sub-orbital, and satellite assets.
- New methods for characterizing specific environmental domain radiation fields using data assimilative techniques in existing coupled modeling systems.
- Coordinated data analysis of radiation belt and plasma sheet measurements in the magnetosphere with upstream solar wind measurements under a variety of geomagnetic-activity conditions and substorm activity.
- Analyses of radiation environment background variability due to galactic, solar, magnetospheric, and atmospheric inputs that lead to fundamentally new insights.

- Analyses that elucidate radiation environment dynamics during energetic particle storms and during geomagnetic storms and that can lead to improved physical explanations as the basis for predictions.
- Development and/or use of first-principles and empirical modeling systems, with data assimilation, to more accurately characterize the current state of the weather of the radiation environment and lay a foundation for its prediction.
- Theoretical and modeling studies that describe the role of space weather drivers causing radiation-environment and charging-environment variability and that demonstrate a capability for prediction at all time scales.
- Innovative use of existing and new data sets that improve our understanding of radiation-environment variability and charging-environment variability.
- New methods for quickly identifying the potential effects on humans and technology from extreme radiation events and that could be integrated into predictive systems.

SSA-IX: Stellar Impacts on Planetary Habitability

Key Elements: Atmospheric Depletion and Stripping, Magnetospheric Shielding, Stellar Winds, Flares and Mass Ejections

Executive Summary

The goal of this SSA is to understand and predict how the stellar activity and the space environment nearby a planet and its moons can impact the conditions that would be necessary for sustaining life. This goal can be achieved by leveraging data from multiple missions throughout our own solar system and state-of-the-art models that the heliophysics community has developed, with an eye towards the expanding field of exoplanetary research and the key factors that control planetary habitability. Additionally, the aim is for these investigations to, in turn, feed back on and improve studies of the heliosphere, by testing current heliospheric models under different astrospheric conditions.

Scope

Through the last couple of decades an increasing number of exoplanets have been discovered in the so-called "habitable zone." However, finding an exoplanet in the habitable zone of a star, which is strictly defined by the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure, does not guarantee that the planet is habitable. The impact of stellar activity and the space environment around a planet and its moons are key factors that can control, through a complicated coupled chain of physical processes, planetary habitability both over short time periods and over periods long enough to support the evolution of life.

One of the key factors that controls planetary habitability is sustaining an atmosphere over long timescales. Despite the wealth of measurements from Earth, Mars, and Venus, we still do not understand the critical factors that determine the ultimate loss of an atmosphere to space. A question that has been at the forefront of solar and extrasolar system science is whether a global planetary magnetic field is necessary for sustaining an atmosphere. On the one hand, a magnetic field can protect the planet from solar/stellar wind stripping. On the other hand, magnetospheric processes lead to acceleration of charged particles and can fill the inner-planetary space with hot plasma. Precipitation of hot plasma particles into the outer layers of the planetary atmosphere changes atmospheric chemistry, temperature, and causes atmospheric depletion. For example, while estimates of the total escape rates for Mars and Venus are on the order of 10^{25} particles per second, estimates for Earth are spread over a wider range from 10^{24} to 10^{26} particles per second mainly due to the complicated ionospheric and magnetospheric processes and pathways for ultimate escape.

Magnetospheric shielding from the stellar/solar activity is another key issue at the forefront of planetary habitability research. Stars directly affect the radiation environment of planets via high-energy radiation, energetic particle events, and the stellar wind, whose properties can range from large-scale transients, such as Coronal Mass Ejections (CMEs), to small-scale turbulence. The impacts of this stellar activity on a planet can vary, depending on the existence or absence of any internal magnetic field. Furthermore, heliospheric/astrospheric shielding from Galactic Cosmic Rays (GCRs) can affect the chemical evolution of atmospheres. Understanding our own heliosphere's interaction with GCRs can help us understand how the field of other stars can determine how much or how little GCRs reach the atmospheres and affect their chemical evolution.

Given the increasing number of exoplanets discovered in the habitable zone, there is an opportunity for the heliophysics community to contribute to the fundamental issue of planetary habitability, and conversely, to test heliospheric models in a variety of stellar environments. Ongoing efforts to constrain the intrinsic magnetic fields of exoplanets through radio observations can draw on quantitative data, as well as assessment and modeling from our own planet and solar system. This area is particularly timely considering the recent launch of the Transient Exoplanetary Survey Satellite (TESS) in 2018, which is expected to significantly increase the number of known exoplanets, as well as future exoplanet missions in development or planning.

Models

The heliophysics community has developed a number of the necessary components of a viable habitability program. Stellar irradiance can now be calculated using available irradiance models and software tools. With new observations of stellar parameters, global heliophysics models can be applied to other stellar systems to characterize the physical properties of the stellar heliosphere and the stellar wind. Current Space Weather capabilities can be utilized to predict the properties and severity of flares, stellar Coronal Mass Ejections, and other activity events. Combined thermosphere, ionosphere, and magnetosphere models have developed to the extent that ion outflow can be described on Earth. With sufficient development and drawing on new observations, similar models can be extended to other planets. This expertise and infrastructure can be readily applied to the study of interactions between exoplanets and their host stars with an eye toward habitability.

Observations

A wealth of data from the space environment and atmospheres of our solar system planets and their moons (Earth, Mars, Venus, Saturn, Titan, Jupiter, Pluto) can be investigated in a comparative aspect, so that the knowledge acquired can enable the characterization of exoplanetary space environments and achieve progress toward our ability to predict the habitability of planets. Detailed observations of magnetospheric emissions from our solar system can be used to build a theoretical framework to obtain order-of-magnitude predictions of frequencies and flux densities of exoplanetary radio emissions.

Predictive Goals / Connections / Products

The goal of this SSA is to improve the understanding of the stellar impacts and the near-planetary space environment on planetary habitability. This Strategic Science Area (SSA) is strongly connected to and reliant upon all of the other LWS program SSAs and has as main goal to bring together the heliophysics community across the solar system, in order to investigate the fundamental, intricately coupled processes that can lead to conditions necessary for sustaining life on a planet.

Example products are: models to constrain magnetic fields of exoplanets; heliophysics models for other stellar systems; thermosphere, ionosphere, and magnetosphere models for other planets

Measures of Success

- Capability to assess the impact of planetary/exoplanetary magnetic fields on atmospheric loss
- Capability to assess the impact of heliospheric/astrospheric magnetic fields on shielding from GSCs
- Capability to assess the impact of planetary magnetic fields on shielding from solar/stellar activity

Types of Investigations

Substantial progress on this Strategic Science Area is possible with the following types of investigations that can be supported:

- Modeling and observational investigations of atmospheric loss in our solar system that can be applied to extrasolar systems.
- Modeling and observation investigations of solar/stellar irradiance and activity and solar/stellar wind activity.

- Modeling and analysis of interactions between the stellar/solar wind and planetary atmospheres.