Living with a Star Program Analysis Group (LPAG) Executive Committee (EC) 2020 Report

June 10, 2021

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1 Committee Membership

LPAG Executive Committee Members

Anthea Coster, MIT Haystack Observatory, Co-Chair
Sabrina Savage, NASA Marshall Space Flight Center, Co-Chair
Joe Borovsky, Space Science Institute
Richard Collins, University of Alaska
Seebany Datta-Barua, Illinois Institute of Technology
Chuanfei Dong, Princeton University
Heather Elliott, Southwest Research Institute, San Antonio
Matina Gkioulidou, Johns Hopkins University Applied Physics Laboratory
Fan Guo, Los Alamos National Laboratory
Brian Walsh, Boston University
Angelos Vourlidas, Johns Hopkins University Applied Physics Laboratory
Shasha Zou, University of Michigan

LWS Program Ex-Officio

Jeff Morrill, NASA Headquarters, LWS Program Scientist
Simon Plunkett, NASA Headquarters, LWS Science Lead
Lika Guhathakurta, NASA HQ
Shing Fung, NASA Goddard Space Flight Center, LWS Website Manager

Liaison Members

Due to the COVID-19 pandemic, the EC meetings were all held virtually, signficantly complicating meeting logistics. Therefore, liaison membership was not included in the 2020 committee discussions but is expected to be re-implemented in 2021.

2 Executive Summary

The NASA Living with a Star (LWS) Program Analysis Group (LPAG) serves as a community-based interdisciplinary forum for soliciting and coordinating community input for Living with a Star objectives and for examining the implications of these inputs for architecture planning, activity prioritization and future exploration. This document is the annual report to NASA Headquarters on the activities of the LPAG Executive Committee in 2020. The discussions this year focused primarily on the development of draft Focused Science Topics (FSTs) (Section 3) with additional reviews of the LWS infrastructure (Section 4) and FST team reporting (Section 5).

The first committee meeting of 2020 was held on May 5 and 7, which was followed by a virtual Town Hall presentation on June 18 to discuss the FST development process with the community. Additional committee meetings were held on July 16 and 17 as well as on September 25. Additional Town Hall presentations were given at the CEDAR and AGU meetings.

Note that due to the COVID-19 pandemic, all meetings and Town Halls were held in virtual settings.

3 Development of draft Focused Science Topics (FSTs)

The committee released a Call for Community Input to LWS Focused Science Topics (FSTs) on May 14, 2020 open until July 3rd, soliciting topics and other feedback through the LWS website. A virtual Town Hall meeting was held on June 18 to engage the community and to clarify the feedback process. A second Call for Community Input was released on October 5, 2020 to announce the additional comment period opened between October 5–23 for feedback on the inital FST drafts. No new topics were accepted during this final comment period.

The committee then finalized the write-ups of 22 draft FSTs, based on two sets of community input and feedback on those draft topics. Incorporated into the final set were 12 roll-over topics from 2018 that have not yet been included in LWS ROSES proposal opportunities. The new FST drafts are appended to the end of this report. (Section 6).

4 Living with a Star Infrastructure

The Living with a Star Infrastructure, emphasizing the LWS focus on Heliophysics interdisciplinary science was presented by Madhulika Guhathakurta at the May and September 2020 LPAG meetings. This included a discussion of the LWS summer school, the Jack Eddy fellowship program, and the LWS institutes. Both at the May and September meetings, the LPAG discussed the import of these programs to the overall goals of LWS.

These LWS programs were all highly rated by the committee. The committee did suggest the possibility of expanding the Jack Eddy post doc program from the current number of ~3 recipients. The Committee also suggested the possibility of an additional year for the Jack Eddy fellowship, which would be more similar to the NASA Postdoctoral Program. The rationale was that almost as soon as the post-doc position started, the Jack Eddy fellow needs to consider his or her next move. The committee also supported the LWS institute program, noting the considerable success of recent institutes in forging new research areas. Currently the Institutes cover travel, per diem, and lodging for two meetings a year. The suggestion of adding some salary support was given.

5 FST Team Reporting

The 2019 LPAG EC report contained findings regarding “Assessing Progress of Focused Science Topics (FSTs) in Addressing LWS Goals”. The EC suggested for NASA Headquarters to request information from the FST teams that could readily be used to track and assess progress of the FST in advancing the LWS goals, preferably in the form of regular, brief, top-level reports that could be made publicly available (without adding undue burden on the FST teams).

To that end, progress has been made by the LWS web development team in constructing a website providing FST team reporting templates based on the reporting structure provided within the 2019 LPAG EC report. This site and reporting format will be reviewed by the EC in the 2021 calendar year.

6 Draft Focused Science Topic Write-ups

The draft FSTs were generated from the 2020 Community Inputs to the FST process. Several unused FSTs from 2018 were rolled over. An Appendix to this report is provided that lists the cross-reference numbers used to identify the individual comments incorporated into each FST (see notes to NASA at end of each FST). The final set of draft FSTs are as follows:

1. Connecting Space Weather and Thermospheric Composition
2. Impact of Terrestrial Weather on the Ionosphere-Thermosphere
3. Multi-scale High-Latitude Forcing on Ionosphere-Thermosphere System
4. Understanding Ionospheric Conductivity and Its Variability
5. Beyond F10.7: Quantifying Solar EUV Flux and Its Impact on the Ionosphere-Thermosphere-Mesosphere System
6. Solar Eclipses as a Naturally Occurring Ionosphere-Thermosphere Laboratory
7. Ion-Neutral Coupling in the Ionosphere-Thermosphere system
8. Pathways of Cold Plasma through the Magnetosphere Pathways of Cold Plasma through the Magnetosphere
9. Connecting Auroral Phenomena with Magnetospheric Phenomena
10. Coupling of the Solar Wind Plasma and Energy to the Geospace System
11. Synergistic View of the Global Magnetosphere
12. Understanding Space Weather Effects and Developing Mitigation Strategies for Human Deep Space Flight
13. Evolution of Coronal Mass Ejections in the Corona and Inner Heliosphere
14. Physical Processes Responsible for the Birth and Evolution of the Solar Wind
15. Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle
16. Solar Flare Energetic Particles and Their Effects in Large Solar Energetic Particle Events
17. Understanding the Transport Processes of Solar Energetic Particles from Their Origins to the Entire Inner Heliosphere
18. Extreme Solar Events — Probabilistic Forecasting and Physical Understanding
19. Towards a Quantitative Description of the Magnetic Origins of the Corona and Inner Heliosphere
20. Understand Energy Partition and Energy Release Processes in Eruptive Events
21. Atmospheric Evolution and Loss to Space in the Presence of a Star
22. Stellar Impact and Extreme Activity on Exoplanetary Atmospheric Loss and Habitability

FST.1 Connecting Space Weather and Thermospheric Composition

This FST addresses the coupling between space weather and atmospheric composition in terms of how changes in neutral composition both respond to and influence space weather events. Solar and geomagnetic storms produce variability resulting in significant variations in atmospheric density and mesoscale structure, and as well as changes in atmospheric composition. With the gradual cooling and contraction of the thermosphere due to increasing carbon dioxide, orbiting debris has a longer lifetime, and continues to accumulate. Understanding thermospheric density and composition changes is crucial and motivates the development of improved atmospheric density and wind models, especially during geomagnetic storm periods. Changes in composition at boundaries, such as auroral and subauroral zones, result in significant regional changes in density and satellite drag.

Space weather events alter the thermospheric state very quickly and produce variability that results in more than four-sigma uncertainty in density. One component of this variability is due to the effect of solar flares on the sunlit side of the earth. Additional variability is a consequence of geomagnetic storms, when most of the geospace energy input to the atmosphere comes through the high latitudes and is associated with significant mesoscale structure. It can take several hours before the heating is globalized. This heating lag contributes to variable drag for different satellites based on the location of their orbit relative to the mesoscale heating region. Constraining the errors in atmospheric density estimates is critical to improving atmospheric drag estimates, and over the long term, to improving the estimation of satellite orbits.

Overview of Science Goals:

The science goals of this FST are to determine how the composition and structure of the thermosphere both respond to and contribute to space weather events; improve physics-based models of thermospheric density; to understand coupling between space weather (ionization and heating) and atmospheric composition (i.e., O/N2 and NO) and resultant changes in structure and transport; to understand this coupling over multiple time scales in quiet time and storm time; and to understand dynamical-chemical coupling of the upper and middle atmosphere, improve satellite drag estimation.

The user communities are the space weather community and the ionospheric and atmospheric research community.

Applicability to LWS within NASA Heliophysics:

This FST addresses how structure, composition and circulation of the ionosphere-thermosphere responds to and contributes to space weather events. It provides contributions to a broad span of LWS Strategic Science Areas (II, IV, V, VII, X).

This FST addresses three of the four Heliophysics Decadal Survey goals: Key Science Goal 2 “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs”; Key Science Goal 3, “Determine the interaction of the Sun with the solar system and the interstellar medium”; and Key Science Goal 4, “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe”.

Envisioned Focused Science Topic Implementation Strategy:

Successful implementation strategies may use coupled efforts of theory, numerical as well as other advanced modeling techniques, data assimilation, and innovative data analysis to the coupling between the thermospheric composition and space weather events. Specific investigations could include: thermospheric response to geomagnetic storms; characterization and comparison of storm time and quiet time variability of the thermosphere; identifying drivers and responses of thermospheric variability using coupled models and observations. New machine learning and assimilation techniques may be applied to understand the response of the thermosphere to space weather events. Appropriate datasets may include GOLD, ICON, COSMIC, TIMED and SWARM, SDO, SOHO, and STEREO.

Implementation strategies could include data analysis, data model comparison, database development, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-overs 165 and 168. No comments.

Check with FST on EUV (ITM5) in terms of addressing EUV impacts on ionosphere-thermosphere.

This FST is focussed on thermospheric composition, some of the drivers of the composition changes are due to the process identified in FST ITM2 (changes to thermospheric circulation and composition are driven by waves and tides).

FST 1, 5, and 7 all have applications to atmospheric drag.

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FST.2 Impact of Terrestrial Weather on the Ionosphere-Thermosphere

Processes generated by terrestrial weather in the lower atmosphere are increasingly recognized as impacting the structure and composition of the ionosphere-thermosphere-mesosphere regions and can contribute to the variability at a similar level as space weather. Terrestrial weather processes generate upwardly propagating waves (gravity waves, tides, and planetary waves) that have a major impact on the variability of the ionosphere-thermosphere. These processes impact both the short-term variability and the mean-state variability of the ionosphere-thermosphere. Statistical analysis of ionospheric observations have shown that lower atmospheric forcing contributes significantly to its variability, and numerical simulations with realistic lower atmosphere variability corroborate these results. Specific investigations have shown that the variability in ionospheric and thermospheric parameters is associated with underlying longitudinal variations of tides and planetary waves, weather systems, sudden stratospheric warmings, and gravity wave hotspots.

This topic is timely for two reasons: (1) modeling has advanced sufficiently to tackle the multi-faceted problem; (2) new data resources exist that allow for detailed model-data comparisons.

New satellite-based observations of the ionosphere and thermosphere by GOLD, ICON, COSMIC2, future missions in development, as well as networks of ground-based instruments (GNSS receivers, ionosondes, radars, lidars and imagers), enable studies of wave influences on the ionosphere-thermosphere system with unprecedented detail. Observations from Aura, Aqua, Terra, and TIMED satellites, as well as MERRA2 reanalysis products, describe spatio-temporal evolution of waves and tides in the middle atmosphere and up to the lower thermosphere.

First-principles numerical models (e.g., WACCM-X, SAMI-3) are now sufficiently advanced to investigate at sufficiently high resolution the mechanisms that contribute to ionospheric and thermospheric variability. Numerical simulations with lower atmosphere variability support realistic investigations coupling pathways and their implications for predictability of the ionosphere-thermosphere and space environment.

Overview of Science Goals:

The science goals of this FST are to determine the contribution of terrestrial weather processes to variability of the ionosphere-thermosphere; to identify the relative role of different waves in driving the ionosphere-thermosphere system; to identify the wave sources, forcing and ionosphere-thermosphere response at different temporal and spatial scales; to identify the role of non-linear wave mean-flow and wave-wave interactions; to identify time scales for predictability of upper atmosphere response to drivers from below; and to develop an improved physics-based understanding of wave forcing in the thermosphere-ionosphere.

The user communities are the space weather community and the ionospheric and atmospheric research community.

Applicability to LWS within NASA Heliophysics:

This FST addresses the pathway for the flow of energy from the lower atmosphere to the geospace environment that contributes to the structure, composition and circulation of the ionosphere-thermosphere. It provides contributions to a broad span of LWS Strategic Science Areas (IV, V, VI, VII).

This FST addresses two of the four Heliophysics Decadal Survey goals: Key Science Goal 2, “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs”; and Key Science Goal 4, “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe”.

This FST also addresses goal 4 of the LWS 10 Year Vision Report: “Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below”.

Envisioned Focused Science Topic Implementation Strategy:

Successful implementation strategies may use coupled efforts of theory, numerical as well as other advanced modeling techniques, data assimilation, and innovative data analysis to understand energy transfer by wave processes from the lower atmosphere into the ionosphere-thermosphere. Specific investigations would include: correlation of ionospheric variability with known meteorological events (e.g., SSW’s, MJO, GW hotspots); longitudinal dependence of ionospheric variability due to planetary waves and tides; generation of ionospheric instabilities; observation-driven investigations from satellites and ground-based systems; interaction of planetary waves, tides, and gravity waves; whole atmosphere model-based investigations. New machine learning and assimilation techniques may be applied to understand wave sources and propagation.

Implementation strategies could include data analysis, data model comparison, database development, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 167 and community input 197 along with four community comments.

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FST.3 Multi-scale High-Latitude Forcing on Ionosphere-Thermosphere System

Coupling processes across scales are important to understand energy redistribution in the Magnetosphere-Ionosphere-Thermosphere system and formation of localized ionospheric density structures that disturb GNSS signals and satellite operations. In addition, multi-scale high-latitude forcing can lead to significant changes in thermospheric composition and density in mid- and low-latitudes. The auroral region is the gateway for energy and particle input from the solar wind and magnetosphere into the atmosphere that drives many of these processes at multiple scales. Auroral drivers embody one of the primary ways in which magnetic reconnection couples to the Earth's ionosphere and atmosphere, acting as the indirect means by which the solar wind connects to near-Earth geospace. As such, they also imprint and reveal physical events at the magnetopause and magnetotail as well as the ionosphere.

Energy transfer processes from the magnetosphere into the ionosphere-thermosphere occur in a variety of forms and scales. These processes include diffuse and discrete aurora and the associated particle precipitations and Poynting fluxes. Physical parameters involved include, but are not limited to, electric fields, neutral winds and density, plasma flows, field-aligned currents (FACs), ionospheric conductance and conductivity, and chemical reactions. Although these energy transfer processes mainly occur in the high latitude, they also generate meridional neutral wind and large-scale travelling atmospheric and ionospheric disturbances (TADs and TIDs) that propagate toward the equator, thereby transferring energy and composition perturbations to lower latitudes.

Bridging the gap from multi-scale electrodynamic forcing at high latitudes to lower latitude and global disturbances in the ionosphere-thermosphere remains an outstanding challenge.

Overview of Science Goals:

The science goals of this FST are to determine how high-latitude multi-scale processes impact the composition, energetics, circulation and variability of the global ionosphere-thermosphere system; to understand how auroral drivers reflect magnetospheric and ionospheric coupling processes; to understand the role of small- and meso-scale drivers in the high-latitude region; and to understand pathways for redistribution of energy in the magnetosphere-ionosphere- thermosphere.

Applicability to LWS within NASA Heliophysics:

This FST addresses the pathway for the flow of energy from the magnetosphere into the ionosphere-thermosphere. It provides contributions to a broad span of LWS Strategic Science Areas (IV, V, VI, VII).

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

Envisioned Focused Science Topic Implementation Strategy:

Successful implementation strategies may use coupled efforts of theory, numerical as well as other advanced modeling techniques, data assimilation, and innovative data analysis to understand how multi-scale high-latitude processes impact the composition, energetics, circulation and variability of the global ionosphere-thermosphere, in particular during geomagnetic storms. Specific investigations would include: neutral density structures and temperature gradients; ionospheric density structures; plasma convection and field aligned currents; traveling atmospheric and ionospheric disturbances; energy deposition and transfer associated with particle precipitation, different types of aurora, ionospheric conductivity and heating; inter-hemispheric processes; coupling into the magnetosphere. New machine learning and assimilation techniques may be applied to understand multi-scale processes. Appropriate datasets may include GOLD, ICON, COSMIC, TIMED, SWARM, RBSP, THEMIS, MMS.

Implementation strategies could include data analysis, data model comparison, database development, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 167 and community inputs 183 and 184 along with 13 community comments.

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FST.4 Understanding Ionospheric Conductivity and Its Variability

Conductivity is an essential physical parameter for the coupling between the solar wind, the magnetosphere, ionosphere, and thermosphere, but is also one of the most difficult parameters to characterize and estimate. It can not be directly observed. It is a complex realization of a number of interconnected phenomena, including energies from the Sun and solar wind, in the form of solar radiation, particle precipitation and Poynting flux, as well as the ionosphere-thermosphere state. Conductivity structures can form during dynamic processes such as auroral disturbances (including both large-scale and small-scale structures), ionospheric and thermospheric disturbances, and large-scale plasma transport.

Because of this inherent complexity, the ionospheric conductivity and its variability are not well understood. Most first-principles numerical models have embedded electrodynamics equations that require knowledge of the horizontal distribution of height-integrated conductivities and their variations to properly interpret the tightly coupled feedback loops between the ionosphere and magnetosphere. However, the vertical structure of the conductivity is widely ignored by these global models, although it is critical for properly characterizing and understanding the high-latitude ionosphere and thermosphere. Recent community work has recognized the need to integrate richly diverse data sets to advance the understanding and prediction of ionospheric conductivity. Developing and validating realistic models for ionospheric conductivity will address this gap and lead to improved predictive models of magnetospheric and ionospheric variations associated with geomagnetic activity.

This topic is timely for two reasons: (1) predictive space weather modeling has advanced sufficiently to tackle the multi-faceted problem; (2) large data resources exist that allow for detailed model-data comparisons at a level not previously possible.

Overview of Science Goals:

The science goals of this FST are the development of realistic ionospheric conductivities either for empirical models or for use in first-principle models. In particular, efforts should focus on conductivity variations driven by dynamical horizontal or vertical structurings in the ionosphere and thermosphere, such as traveling ionospheric disturbances, thermosphere composition change, and physical processes at high latitudes and magnetosphere that can improve the description of energetic electron and ion precipitations. An additional goal of this FST is to assess to what degree each of the above parameters affect the overall magnetosphere–ionosphere coupling during geomagnetic activity. The communities that will most directly benefit from these activities include the magnetospheric and ionospheric communities but ultimately the entire space science community will benefit.

Applicability to LWS within NASA Heliophysics:

This FST is relevant to several LWS Strategic Science Areas in relation to ionospheric connectivity (IV, V, VII, VIII).

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

Envisioned Focused Science Topic Implementation Strategy:

Methods, data sources, physics models and types of investigations are needed to address this FST. Data analysis studies should be coordinated with theoretical and numerical modeling studies, especially for assessing the effect of realistic conductivity on global magnetospheric models and ionosphere-thermosphere models. Data implementation strategies may consist of conductivity-focused analysis of space-borne datasets (e.g., GOLD, COSMIC, GNSS, CHAMP, DMSP/SUSSI, TIMED/GUVI, AMPERE) coupled with datasets from ground-based facilities such as Incoherent Scatter Radars (ISR), ionosonde, SuperDARN, and SuperMAG. Note that joint analysis methods are encouraged to provide system-scale information. For example, some of these assets provide important, but indirect, large-scale information (e.g., integrated ionospheric density distributions from GNSS total electron content), and studies that can integrate the traditionally disparate fields (e.g., IT variability and magnetospheric dynamics) should be prioritized.

Potential types of investigations include:

- development of methods, including assimilative and machine learning ones, that combine some or all of the observational assets in order to produce the 3D conductivities at different latitudes;
- investigations that ingest improved conductivity descriptions into numerical models and assess their impact on the magnetosphere–ionosphere coupling processes;
- modeling investigations of improved particle precipitation description on the 3D conductivity structure and the feedback on the magnetosphere;
- modeling investigations of ionospheric processes (e.g., turbulence) producing conductivity variations beyond those driven by solar radiation and precipitation;
- quantification of feedback pathways between ionosphere and magnetosphere due to structured conductivity;
- investigations of conductivity variability due to large scale plasma transport (e.g., tongue-of-ionization and patches), and its potential feedback on the magnetosphere;
- investigations exploring the coupling of high- and mid-latitude conductivities (auroral) to low-latitude ones (equatorial), during geomagnetic disturbances.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 169 with three community comments.

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FST.5 Beyond F10.7: Quantifying Solar EUV Flux and Its Impact on the Ionosphere-Thermosphere-Mesosphere System

Solar extreme-ultraviolet (EUV) flux is a dominant heating and ionization source for the ionosphere-thermosphere-mesosphere (ITM) system. Solar activity fluctuates on several temporal scales – from minutes (flares) to days (27-day rotation) to decades (11-year cycle) – and initiates huge variations in the neutral density and temperature, ion and electron densities and temperatures, neutral winds, and electric fields in the ionosphere. Studies of the ITM often rely on the F10.7 index (solar radio flux at the wavelength of 10.7 cm) as a primary solar driver. This index does not directly describe the solar input in the EUV wavelength range below 102.5 nm that is directly responsible for much of the ionization of the thermosphere.

Solar flares have a profound effect on the ITM system. With satellite EUV data from numerous observational datasets (SOHO/SEM, TIMED/SEE, SDO/EVE, GOES/EXIS), indices (e.g., S10.7, Y10.7, Mg II, Lyman-Alpha) and new proxies from solar irradiance models (SIP E10.7, FISM2 EUV) have become available within the last two decades. These indices and measures can better characterize solar energy input to the thermosphere than the traditionally used F10.7 index.

The impact of EUV using these improved indices has been studied in the thermosphere, and their usage substantially improves thermospheric density models. However, the impact of these indices on different ionospheric parameters (peak density of the F2 layer NmF2, total electron content (TEC), electron density in the D-region and topside ionosphere, nitric oxide) is much less known. Predictive capability requires detailed knowledge of the physical processes by which solar forcing impacts the IT system.

Overview of Science Goals:

The overarching goal of this FST is to develop the ability to reliably predict the effects of solar variability on the ionosphere, thermosphere, and mesosphere (ITM). Specific goals include examining whether these new indices are better suited for driving empirical model predictions of ITM structure. Another goal is to investigate how particular portions of the EUV spectrum influence the ionospheric profile shape and behavior of thermospheric density and temperature. Interactions between the ionosphere and thermosphere simultaneously driven by alternative EUV measures are also of interest. Studies that validate new predictions of ITM properties against measurements will be necessary to evaluate the success of alternatives to F10.7. Studies that respond to high-cadence variations in EUV, e.g., solar flares, and their impact on ITM processes will improve our understanding at sub-daily time scales.

Applicability to LWS within NASA Heliophysics:

This FST is relevant to several LWS Strategic Science Areas in relation to the impact of solar EUV flux variability (I, II, V, VII).

This FST directly addresses Key Science Goal 2 in the 2012 Solar and Space Physics Decadal Survey: “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.” It also directly responds to Goal 4 of LWS 10 Year Vision Report: “Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below.” Progress made during this FST will be applicable to understanding the atmospheres and ionospheres of other planets and exoplanets. Results of this FST will also have high societal relevance as they will improve models and observations that support the major effort to develop space traffic management.

Envisioned Focused Science Topic Implementation Strategy:

This FST encourages the use of data, theory, models and simulation, development of tools and analysis techniques in combinations necessary to address the science goals. Proposals to this FST are welcome to leverage advances brought by observations from multiple NASA satellites and contribute to overarching community goals that are beyond any single satellite mission. This topic is timely, as modern satellite data (TIMED/SEE, SDO/EVE, GOES/EXIS) provide measurements with high spectral resolution and high temporal cadence and can be used to gauge the solar inputs. New satellite-based observations of ionosphere and thermosphere by GOLD, ICON, COSMIC, as well as networks of ground-based instruments (GNSS receivers, incoherent scatter radars, ionosondes) enable studies of solar flux influences on the ITM system with unprecedented detail. Studies may focus on which wavelengths are most effective at causing ITM variations, which wavelengths produce which effects, e.g. enhanced plasma drift, TEC changes. Investigations that may firmly establish a correlation between EUV flux variations and ionospheric response, which may enable TEC measurements as an effective monitor of solar flare ITM effects, are encouraged.

Modeling and model validation, both in EUV flux specification and in ITM modeling as driven by EUV flux are encouraged. For instance, the EUVAC model has 39 bands but is driven by the single F10.7 index. New EUV spectral models (e.g. Solar Irradiance Platform (SIP), FISM-2) have been developed and are driven by multiple observations, not just a single F10.7 proxy. Models with high spectral resolution and temporal cadence might be tested for applicability to first-principles models of the ITM system. Proposals might investigate the strengths and weaknesses of new solar spectral models for specification of irradiance and prediction of ionospheric and thermospheric parameters. New machine learning techniques may be applied to improve the information content of irradiances, indices, and proxies in historical or forecast time horizons. This FST will also engage research groups that work on different aspects of heliophysics research and will promote interdisciplinary collaboration.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a new addition from community input 196.

FST 1, 5, and 7 all have applications to atmospheric drag.

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FST.6 Solar Eclipses as a Naturally Occurring Ionosphere-Thermosphere Laboratory

Solar eclipses provide unique opportunities to examine ionosphere-thermosphere (IT) coupling as the moon's occultation of the sun casts a shadow in solar irradiation that sweeps through the Earth's atmosphere at supersonic speed. Solar eclipse effects on the IT system are caused primarily by this sudden reduction in solar irradiation. Photo-ionization and photo-absorption rates of the ionosphere and thermosphere abruptly change.

Eclipses are a naturally occurring "controlled" experiment against which to test predictions of the effects of abrupt transient radiation variation effects on the atmosphere. Results from the 2017 North American solar eclipse led to animated debate into the causes of wavelike perturbations in IT physical properties, whether due to supersonic motion of the umbra across the IT or due to the abrupt cooling coupled with processes such as mountain waves and convective waves from below and their amplification with altitude.

There is renewed community interest in eclipse-induced IT variations due to the recent expansion of capabilities in observation and modeling of the upper atmosphere. With the availability of space-based observations such as GOLD, ICON and COSMIC II, ground-based total electron content (TEC) data, and advances in global geospace modeling, the space research community has a new opportunity to further explore the dynamic, electrodynamic, and chemical processes that govern the behavior of the whole geospace during transient solar radiation events, including solar eclipses, that has not been fully understood so far. With a total solar eclipse in Antarctica in December 2021 and the next total solar eclipse over North America in 2024, an FST that develops predictions that are testable will have an eclipse for validating those predictions within the FST project duration. The 2024 North American eclipse also provides an opportunity for significant outreach on the significance of Heliophysics science, in a way that can be directly experienced by the public.

Overview of Science Goals:

This topic is fundamental to understanding geospace responses to transient solar radiation changes. A number of new science questions regarding fundamental IT coupling processes have been raised. Investigations pursuing one or more of the following goals are invited: (1) traveling ionospheric and atmospheric waves (TIDs/TADs), excited by an eclipse, some of which form a bow wave(s) in the thermosphere and ionosphere; (2) hemispheric coupling or the conjugacy of the eclipse effects; (3) solar eclipse influences on the neutral and electromagnetic dynamics, of particular significance at low and equatorial latitudes; (4) solar-eclipse-induced neutral composition change; and (5) high latitude solar eclipse influences on the ionosphere-magnetosphere coupling. Investigations that seek to address outstanding questions arising from previous eclipse-IT science findings are welcome.

Applicability to LWS within NASA Heliophysics:

This FST is relevant to two LWS Strategic Science Areas in relation to IT variability in response to solar eclipses (V, VII).

The FST aligns with the second part of the Decadal Survey science goal 1, "Determine the origins of the Sun's activity and predict the variations in the space environment," because an eclipse provides a specific and predictable change to the solar electromagnetic flux input into Earth's space environment. This FST also aligns with science goal 2, "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere,and atmosphere and their response to solar and terrestrial inputs," by identifying the key interactions and subsequent feedbacks between charged and neutral particle populations when the heating and ionization source is temporarily removed. Solar eclipses provide an opportunity to answer the Decadal Survey's science challenge "AIMI-2 Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system," since local, regional, and large-scale effects are seen along and beyond the umbral path. This FST can also interrogate Decadal Survey challenge "AIMI-3 Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves influences the ionosphere and thermosphere" since it is possible that phenomena observed during the eclipse may result from the direct removal of energy in the IT system and indirectly for the effects in other layers of the atmosphere that then may propagate upward.

Finally, the Living With a Star program is concerned with "how the variability [of the sun] and response [of Earth] affects humanity in Space and on Earth." Solar eclipses have been an effect long recorded throughout history, and provide the public a chance to directly and simply see a natural phenomenon involving the Heliosphere. This FST provides a key chance for public outreach and a means to engage and broaden the number and variety of citizen scientists with interest and enthusiasm for the science of LWS.

Envisioned Focused Science Topic Implementation Strategy:

This FST will benefit from a variety of strategies and tools. Use of observations collected during past solar eclipses, development of databases aggregating past ground- and space-based data, or planned fieldwork are welcome. Comparisons of IT model predictions on the launch and propagation of waves and disturbances, of the time scales of the transient effects, of conjugate point studies are encouraged, along with their validation against data. Simulations of ionization and absorption processes and their effect on the bottomside ionosphere, peak density and height, or topside density and temperature are relevant. Re-analyses and assimilation of data such as TEC from past events, or proposed future experiments, are encouraged. Observational investigations might be conducted that use satellite-based in situ or remote measurements of IT parameters including neutral wind speeds and temperatures, plasma densities and temperature, correlated with variation in emissions. Theories of traveling wave propagation and on origination of disturbances, and development of models that can disentangle TID/TAD generation from the eclipse from those generated from sources in the lower atmosphere are all also relevant. Implementation strategies could include data analysis, data model comparison, database development, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a new addition from community input 198.

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FST.7 Ion-Neutral Coupling in the Ionosphere-Thermosphere System

The dynamic interaction between plasma and neutrals in the upper atmosphere impacts how the ionosphere responds to changes in the thermospheric wind, composition and temperature, and how the thermosphere dynamics and thermal status are affected by the plasma electrodynamics. A critical component of these ionosphere-thermosphere (IT) interactions is a variety of ion-neutral coupling processes. For example, coupling across interfaces is especially strong in the presence of magnetic fields. At these interfaces, mass, momentum, and energy transfer are highly efficient. Where ions are magnetized, ion-neutral collisions may be the dominant way to convert fast ordered motion into heat, likely a major source of heating for the ionosphere and thermosphere. Addressing unresolved issues involving ion-neutral coupling within the IT system is the focus of this FST.

Significant gaps exist in our understanding of how ion-neutral coupling forms ionospheric features such as the equatorial anomalies of the neutral density, temperature, and wind. Additional gaps in our knowledge include the ionospheric variations known as the Weddell Sea Anomaly (WSA) and the summer night anomaly. Storm-time processes producing the neutral upwelling caused by energy deposition in the thermosphere are also not fully understood, although its effect on the global storm time IT perturbation has been observed. In all of the above examples, how the exchange of momentum, energy, and charge occurs is the area that more progress is needed. This topic has important societal relevance to navigation/communication and tracking and reentry prediction of artificial satellites. The next strategic LWS mission, GDC, will benefit strongly in its plans for implementation, both in its development and analysis of its results, if this fundamental phenomenon is understood better in the near-term.

Overview of Science Goals:

The specific science goals of this FST are divided into different latitudinal regions.

For ion-neutral coupling in the equatorial region, the science goals are to address questions relating to the characterization of the neutral density, temperature, and wind anomalies and their association with the equatorial ionosphere dynamics.

For ion-neutral coupling in the middle latitudes, the science goals are to understand ionospheric climatological phenomena such as summer evening ionospheric density enhancement and WSA and to elucidate the roles of the neutral winds and composition, electric fields, and the topside plasma influx.

For ion-neutral coupling in the sub-auroral and high-latitude regions, the science goals are to characterize the neutral wind changes, and potentially composition changes, associated sub-auroral high speed polarization streams (SAPS); to study the high latitude winds driven by plasma convection; the global circulation changes driven by upwelling that impact the storm-time composition, winds, and the disturbance neutral wind dynamo, and the relationship of storm generated traveling atmospheric disturbances (TADs) to traveling ionospheric disturbances (TIDs).

Applicability to LWS within NASA Heliophysics:

This FST is relevant to two LWS Strategic Science Areas in relation to IT coupling in the IT system (V, VII).

This FST aligns with science goal 2 of the Decadal Survey, “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere,and atmosphere and their response to solar and terrestrial inputs,” by identifying the key interactions and subsequent feedbacks between charged and neutral particle populations when the heating and ionization source is temporarily removed. It also directly responds to Goal 4 of LWS 10 Year Vision Report: “Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below.” Results of this FST will also have strong societal relevance as they will improve models and observations that support the atmospheric drag modeling for traffic management.

Envisioned Focused Science Topic Implementation Strategy:

This FST would rely on data analysis, data model comparison, simulations, theory and model development, tools and analysis techniques, and other investigations. Successful implementation strategies may use coupled efforts of theory, numerical as well as other advanced modeling techniques, data assimilation, and innovative data analysis for the coupling between the thermospheric composition and ionospheric density. Satellite-based observations of ionosphere and thermosphere by GOLD, ICON, COSMIC, TIMED and SWARM as well as networks of ground-based instruments (GNSS receivers, incoherent scatter radars, ionosondes, FPIs, all-sky imagers, riometers) will provide required measurements. Specific investigations could include: thermospheric response to geomagnetic storms; drivers and responses of thermospheric variability using coupled models and observations.

Implementation strategies could include data analysis, data model comparison, database development, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:LWS Strategic Science Areas

This FST is a new addition from community input 200. There was a ROSES 2009 call on Neutral Gas Coupling.

FST 1, 5, and 7 all have applications to atmospheric drag.

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FST.8 Pathways of Cold Plasma through the Magnetosphere

Low-energy (< 1 keV) ions and electrons play significant roles in the magnetospheric system. This plasma often dominates the number density and mass density of the magnetosphere. Consequently, it alters the plasma waves that reside in the magnetosphere and thereby alters the wave coupling between other plasma populations: the ring current, the electron radiation belt, substorm-injected electrons, plasma-sheet ions, and plasma-sheet electrons. Low-energy magnetospheric plasma can also mass-load dayside reconnection and alter solar wind/magnetosphere coupling.

Overview of Science Goals:

Low-energy plasma in the magnetosphere takes many forms with a variety of sources and time-histories. Two populations that have been proposed to play important roles are: (1) the cold plasmasphere and its drainage plume and (2) the plasma cloak. The plasmasphere has received significant attention, although there are still important outstanding questions. The plasma cloak is less studied and is in need of basic surveys to establish its origin, evolution, and composition as a function of space and time. Other cold-particle populations in the magnetosphere include (3) the electrons and ions of the polar wind, (4) outflowing ionospheric electrons driven by charge neutrality, (5) charge-exchange-byproduct protons, and (6) the hypothetical structured cold electrons of the diffuse and pulsating aurora.

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

The source of the plasma cloak has not been firmly established. The ionospheric-outflow mechanisms involved are not known and neither are the magnetospheric and solar-wind parameters that control the outflow. Basic questions of the cloak's source concern where, when, and how much? Information about the evolution of the cloak plasma carried by magnetospheric convection, during active times and as activity ceases, is needed.

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

This FST concerns the complex feedback between ionospheric outflows and magnetospheric plasma on the coupling of the solar wind to the system. The outstanding issues above are summarized into four objectives of the FST: 1) establish a more accurate understanding of the physics involved in the refilling of the plasmasphere from the ionosphere, and to determine the ionospheric source of the warm plasma cloak and the factors controlling the source; 2) establish a characterization of the evolution of the plasma cloak and make an assessment of the impact that it has on the magnetospheric system; 3) determine the existence and amount of recirculation of the low-energy plasmas from the dipolar region into the magnetotail and assess the impact that any recirculation may have on the magnetospheric system; and 4) determine the properties and controlling factors of the other low-energy electron and ion populations of the magnetosphere.

Applicability to LWS within NASA Heliophysics:

This FST concerns the complex feedback between low-energy magnetospheric plasma from the ionospheric outflows and the coupling of the solar wind to the system and thus applies to two LWS Strategic Science Areas (IV, V).

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

Envisioned Focused Science Topic Implementation Strategy:

This FST will involve coordinated research efforts between ionospheric, thermospheric, and magnetospheric researchers. The main focus is the complex feedback between magnetospheric plasma (from ionospheric outflows) and the coupling of the solar wind to the system. The strategies needed to achieve the first goal of this FST include: efforts to improve models utilizing first-principle plasmasphere-refilling simulation capabilities, and efforts to test these simulations with magnetospheric spacecraft observations. Obtaining the best experimental measures of refilling rates and the factors that govern the rates is part of these strategies: innovative methods may be necessary to obtain the parameters of the plasmaspheric plasma. Plasma-physics and atmospheric-physics expertise will be involved as well as both theory and observation.

Strategies needed to achieve the second goal of this FST include: surveys of low-altitude and equatorial spacecraft measurements from multiple missions in coordination with global magnetospheric modeling and machine learning to characterize the evolution of the plasma cloak.

Strategies needed to achieve third goal are spacecraft observations of low-energy ions in the low-latitude boundary layer, high over the polar cap, in the mantle, and in the night-side plasma sheet to determine the ultimate fate of magnetospheric low-energy plasma after it reaches the dayside magnetopause. In searching for recirculated cold plasma, heating of the cold plasma as it exits the dipolar region must be considered. Strategies needed to achieve the fourth goal include cold ion and cold electron data surveys, perhaps with machine-learning data analysis to produce empirical models of these populations.

Spacecraft observations of the refilling plasmasphere in the magnetosphere will be needed for the first goal. Spacecraft observations of the cloak in the magnetosphere and of ionospheric outflows from the ionosphere will be needed for the second goal. Spacecraft observations in the low-latitude boundary layer, over the polar cap, and in the magnetotail will be needed for the third goal. Spacecraft observations of the polar wind and low-energy ions and spacecraft observations of the total electron number density will be needed to achieve the fourth goal. Potential missions involved are Van Allen Probes, THEMIS, FAST, POLAR, LANL, MMS, Cluster, and Dynamics Explorer.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 166 with six community comments.

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FST.9 Connecting Auroral Phenomena with Magnetospheric Phenomena

It has been a longstanding aspiration to use images of the aurora to help understand and interpret the corresponding dynamics in the magnetosphere. Two critical issues stand in the way of realizing this powerful capability: (1) uncertainty in the mapping of the magnetic dynamics between the ionosphere and the magnetosphere; and (2) lack of detailed knowledge about what processes in the magnetosphere produce the various types of aurora.

Aurorae are ultimately powered by the solar wind driving magnetospheric convection. The optical aurora phenomena represent a critical path for transfer and conversion of energy from the magnetosphere to the ionosphere-thermosphere system, which also drives ionospheric currents, energizes particles, ionizes the thermosphere, heats the ionosphere and thermosphere, removes particles from the magnetosphere, and powers ionospheric upflows/outflows. In addition to removing energy from the magnetosphere, aurora associated energy extraction and ionospheric outflows can alter the plasma content and entropy of magnetospheric flux tubes and affect the magnetospheric dynamics.

All types of aurora involve an interplay of magnetosphere–ionosphere coupling to some degree. Some types of aurora are associated with enhanced levels of magnetospheric convection during geomagnetic disturbances, such as storms and substorms, while other types of aurora are suggested to be related to magnetospheric instabilities, magnetic reconnection, or the local feedback of ionosphere to magnetospheric energy input.

Typical auroral forms spanning from the polar cap to the auroral equatorward boundary include, but are not limited to: polar cap arcs, poleward boundary intensifications, streamers, quiet and growth-phase arcs, omega bands, westward traveling surge, giant undulations, pulsating patches.

Overview of Science Goals:

The goals of this FST are to determine what processes in the magnetosphere are responsible for various types of aurora observed in the low altitude; to assess the energy conversion processes associated with auroral forms and to assess the impact that these auroral processes have on the coupled magnetosphere, ionosphere, and thermosphere system; and to improve or establish high-fidelity magnetic mapping between the low altitude aurora and the source location in the magnetosphere.

Applicability to LWS within NASA Heliophysics:

The first LWS program objective concerns the response of the magnetosphere- ionosphere-thermosphere system to the solar wind driving. This FST deals with the complex transformation of energy in the magnetosphere that gives rise to visible manifestations in the atmosphere and thus is directly relevant to the above LWS program objective. Subsequently, this FST is applicable to a broad span of LWS Strategic Science Areas (IV, V, VI, VII).

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

Envisioned Focused Science Topic Implementation Strategy:

The implementation strategy and methodologies envisioned for this FST involves:

- Coordinated research efforts involving auroral observations, ionospheric diagnostics, and magnetospheric in situ measurements, aided by theory, regional and global numerical modeling, to generate holistic thinking of aurora dynamics;
- the development of innovative methods to determine and improve the magnetosphere-ionosphere magnetic connections;
- the development of innovative quantitative methods to determine the spatial extent and temporal evolution of dynamic aurora forms;
- assessment of energy conversion and field-aligned-current generation in magnetospheric-ionospheric numerical simulations;
- research efforts studying the statistical connections between auroral occurrence and observed magnetospheric processes;
- research efforts studying the connections between low-altitude particle measurements and those made in the equatorial magnetosphere.

Potential missions involved for in-situ measurements are POLAR, FAST, THEMIS, MMS, Dynamics Explorer, DMSP, LANL geosynchronous satellites, and Van Allen Probes. Potential missions involved for auroral images are IMAGE, POLAR, Dynamics Explorer, DMSP, as well as higher-resolution ground-based observations, such as the THEMIS ASI array and TREx.

Measures of success could include:

- The capability of predicting auroral forms under certain magnetospheric conditions;
- Multi-event or statistical analysis establishing the relationship between certain type of aurora and their magnetospheric driver;
- Numerical modeling to reveal the magnetospheric dynamic process responsible for certain types of auroral form.
- The development of methods to magnetically connect magnetospheric phenomena to the various observed auroral forms.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 171 with three community comments.

Relevant non-NASA ground-based and/or spacecraft data sets may not be available via publicly accessible websites and need to be transitioned into a public forum.

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FST.10 Coupling of the Solar Wind Plasma and Energy to the Geospace System

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

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

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

Overview of Science Goals:

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

Applicability to LWS within NASA Heliophysics:

This FST outlines a central pathway for the flow of energy from the Sun to the geospace environment. It provides contributions to a range of LWS Strategic Science Areas (IV, V, VIII).

This FST supports two of the four high level science goals of the Heliophysics Decadal survey: "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs;" and "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe."

The FST also has timely relevance for the upcoming TRACERS mission.

Envisioned Focused Science Topic Implementation Strategy:

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

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

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 174 with four community comments.

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FST.11 Synergistic View of the Global Magnetosphere

The magnetosphere is composed of and behaves as a system of interconnected parts. Global structure and magnetospheric reconfiguration during geomagnetic storms and substorms is a function of many coupled pathways and plasma populations. Study of individual components or processes isolated from the full body provides a limited scope. This FST focuses on system study of the global magnetosphere and efficient extraction of system-level information and physics from imaging, multipoint measurements, and numerical models.

Overview of Science Goals:

Understanding the global structure of the magnetosphere and its changes during storms and substorms is extremely difficult, because the magnetosphere is sparsely sampled by in situ observations. At any moment there are fewer than a dozen dedicated probes beyond LEO. As a result, it remains unclear:

1. What are the global storm/substorm distributions and time variations of magnetospheric electric currents, plasma pressure and density, and how well can they be reproduced with models and remote sensing measurements, given the extreme scarcity of in-situ observations?
2. What are the feasible and appropriate methodologies for combining global images of the magnetosphere, its global simulations and empirical reconstructions obtained using modern machine learning methods?

Applicability to LWS within NASA Heliophysics:

This FST will contribute to 1) describing, understanding, quantifying, and predicting (including the error analysis) short- and long-term magnetospheric variability and reconfiguration associated with local- and global-scale dipolarizations, magnetic substorms, storms; 2) understanding and forecasting the global state of the ionosphere and its connection with the plasmasphere; and 3) developing science-based predictions of the dynamic radiation environment and spacecraft-charging environment, because those features critically depend on the global structure of the magnetosphere. As such, the FST is relevant to a range of LWS Strategic Science Areas as a system-level view of the magnetosphere (IV, V, VIII).

This FST supports two of the four high level science goals of the Heliophysics Decadal survey: 1) “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs” by determining the global structure of the magnetosphere as a space weather umbrella, its gaps and variations in response to weather anomalies; and 2) “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe” by helping to understand the impacts on the global magnetosphere of the solar wind and underlying magnetic reconnection and quasi-viscous interactions, plasma turbulence, shocks and interaction with neutrals (via the global imaging, first-principles simulations and empirical models).

Envisioned Focused Science Topic Implementation Strategy:

The goal of this FST is to address the science goals stated above using various techniques of the “global vision” of the magnetosphere. Examples of the global vision are Energetic Neutral Atom (ENA) emissions of the hot plasmas in the ring current, EUV plasmaspheric images, soft X-ray images, radio tomography, field-aligned current maps obtained from constellations of LEO spacecraft, similar maps from ground-based radars, all-sky cameras, space-borne auroral imagers, and ground-based magnetometer networks. With the implementation of constellations of spacecraft, both from commercial groups and missions developed with science objectives, it is important for the community to extract a system of understanding, which could be derived from data assimilation models or other learning methods.

A complementary approach may be to employ global first-principle models to describe the magnetospheric structure and evolution, linking solar wind perturbations to global changes in the magnetospheric structure and their ultimate space weather impacts, such as solar energetic particle fluxes, perturbations of the ionosphere and thermosphere, radiation belts, and geomagnetically induced currents.

Finally, historical databases of in situ spacecraft observations (e.g., the geomagnetic field or cold plasma density in the plasmasphere) or extended LEO observations of near-Earth regions can be mined to build sophisticated empirical models (e.g., artificial neural networks) that learn from data and improve as the data volume increases (a distinctive feature of machine learning).

All of these approaches are now sufficiently mature but remain limited in their capabilities if taken alone. It is, therefore, particularly timely to establish an FST team with a balanced mix of experts in the corresponding areas to attack the problem of the characterization of the magnetosphere as a global system in a concerted and synergistic fashion.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of community input 185 along with community comments.

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FST.12 Understanding Space Weather Effects and Developing Mitigation Strategies for Human Deep Space Flight

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

Notably, NASA is surging forward with the Artemis program to re-establish a human presence in lunar orbit as well as a human footprint on the lunar surface. As such, it is of paramount importance that we understand the solar impacts within and around the lunar environment, which has significant localized variation as the moon orbits the Earth (e.g., day side solar energetic particle impacts versus high-Voltage-charging conditions in the lunar wake). Therefore, developing an adaptable and robust model for describing the particle and radiation environment in locations occupied by humans and associated critical resources at these lunar locations is needed in the near term.

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

Overview of Science Goals:

The ultimate goal of this FST is to pull together the relevant information from other FSTs and science results from relevant research groups to provide the information needed to protect astronauts and space assets. Critical needs, applicable to both in-transit and at the final destination for prolonged periods, include solar radiation background level biological hazards that vary with the solar cycle and with dynamic space weather events; high energy particle exposure risks associated with solar eruptions and anomalous galactic cosmic ray flux (insofar as they are part of the background radiation population); and mitigation strategies for predicting and protecting against harmful exposure.

Applicability to LWS within NASA Heliophysics:

The SSA architecture was expanded in 2018 to include the deep space environment addressed by this FST, which is primarily encompassed by SSA-VIII. Understanding the time-varying environments through which astronauts and hardware traverse also requires close integration with several other LWS Strategic Science Areas (I, II, III, IV, V, VIII).

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

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

Envisioned Focused Science Topic Implementation Strategy:

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

Implementation strategies could include data analysis, data model comparison, simulations, and theory and model developments.

Notes to NASA:

This FST is a merger of 172 (roll-over) and community input 182 (plus new comments).

In order for this FST to map back to LWS priorities, the SSA-6 was revised to SSA-VIII in 2019 (Radiation and Particle Environment from Near Earth to Deep Space). The revisions were made to include the deep space environment and its applicability to human deep space travel (a critically and timely topic). This addition is a natural progression of the priorities that the LWS program has undertaken since its inception, expanding from first principles to human application as we undertake efforts to travel beyond low-Earth orbit for extended durations.

Space weather impacts on the Earth will always be a primary focus of Heliophysics and LWS, but for our discipline to thrive in the future it must enroll itself and find relevance to the future of Space Exploration.

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FST.13 Evolution of Coronal Mass Ejections in the Corona and Inner Heliosphere

Fast coronal mass ejections (CMEs) are the major driver of the most intense space weather. There are now more coronal and inner heliospheric observations than ever before. Recent advances in observing CMEs with heliospheric imagers has narrowed the gap between studies focusing on remote observations in the corona vs. investigation of the in situ properties of CMEs. In situ observations from Parker Solar Probe (PSP) and Solar Orbiter (SolO) close to the Sun, combined with simultaneous radio observations and wide angle imaging, help to close this gap. Upcoming missions are also expected to provide both speed and density information along with polarized imaging of the corona and heliosphere. Radio scintillation observations provide column density, the velocity in the plane-of-the-sky, and occasionally magnetic field and density information along the line-of-sight (through the use of Faraday rotation and scintillation techniques), including the level of turbulence in the solar wind upstream of the transient. Global heliospheric models use synoptic photospheric magnetographic inputs to describe the 3-D magnetic field that is integral to solar wind flows and propagation of space weather events through the background fast and slow wind.

One-to-one mapping and tracking from solar observations to measurements at 1 AU is challenging due to the evolution of CMEs and the background solar wind that occurs over a wide range of scales. In addition to the tracking of solar wind features in remote sensing observations, the PSP and SolO in situ magnetic field and composition measurements at intermediate distances between the Sun and 1 AU are critical for testing the tracking of CMEs, mapping, and determining the background source regions. This uniquely comprehensive collection of in situ and remote observations combined with modeling provides a wealth of information on CME evolution across scales but makes it challenging to synthesize and interpret all information.

Team work is needed to determine how CME properties and geo-effectiveness depend on solar conditions, initial state, propagation, and evolution through the corona and heliosphere. This FST is timely given these exciting comprehensive in situ, imaging, and radio observations spanning the corona and inner heliosphere have recently become available.

Overview of Science Goals:

The overarching goal of this FST is to advance our understanding of CMEs, CME evolution, and space weather impact of CMEs as well as to improve heliospheric models, data analysis, and assimilation techniques, within 1 AU heliocentric scales. Objectives include determining how CME properties are affected on their journey through the corona and inner heliosphere as they interact with background structures, and investigating the geo-effective potential of CMEs.

Measures of success could include:

- Creation of a tool, assimilation, combined assimilation and simulation, or simulation that successfully spans multiple spatial scales and improves the understanding of CME evolution in the corona and inner heliosphere.
- Develop a new capability to examine the evolution of CMEs and their substructures as they transit the corona and inner heliosphere and interact with the background wind.
- Integrating or modeling new observations or a new combination of observations to extract additional physical information about the evolution of CMEs in the corona and inner heliosphere.

- Develop a technique or simulation capability that leads to improved forecasts of the space weather impact on the Earth system as a result of improved understanding of CMEs and their evolution through the corona and inner heliosphere.

Applicability to LWS within NASA Heliophysics:

This FST addresses a range of LWS Strategic Science Areas (I, II, IV), focusing on physics-based understanding of CME evolution in the corona and inner heliosphere, development and evolution of the background solar wind, and improving the accuracy of modeling, data analysis, and assimilation techniques that can also be used to forecast space weather.

Envisioned Focused Science Topic Implementation Strategy:

This goal can be achieved through new science investigations combining modeling, remote and in situ data analysis, and the development of new tools and techniques, such as data assimilation as well as joint in situ and remote models. The use of Artificial Intelligence (AI) and Machine Learning (ML) are encouraged (but not required) in this FST.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a combination of community inputs 190, 191, and 187.

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FST.14 Physical Processes Responsible for the Birth and Evolution of the Solar Wind

One of the primary goals of the LWS program is to understand how the Sun influences the Heliosphere and, in particular, interacts with the Earth's environment. Accomplishing this requires a more fundamental understanding of how the time-dependent solar wind is produced and how it evolves as it propagates through interplanetary space to 1 AU. With the successful launch of Parker Solar Probe (PSP) and Solar Orbiter (SolO), and the remarkable new imaging datasets being returned, our community is in a unique position to identify and interpret new phenomena, as well as to better describe previously observed phenomena. Additionally, advances in both local and global numerical models, as well as new or refined theories, are providing tantalizing ideas to explain these new observations and make substantial breakthroughs in our understanding of the underlying processes that modulate the properties of the solar wind. This FST seeks team-developed research efforts to understand the physical processes acting in the creation and inner-heliospheric evolution of the solar wind.

To make effective progress, a team-centric approach is required that seeks to identify all possible candidate processes then builds hypotheses that can be used to support or refute them based on all relevant data and model results. For example, how are blobs, switchbacks, jets, and plumes formed? What role does interchange reconnection play in the generation of the solar wind? Do jets and jet-like phenomena make a significant contribution to the energy and mass of the solar wind? Where do the Alfvenic fluctuations of the solar wind come from? What controls proton, electron, and minor ion heating in the solar wind? What is the origin of drifting beams? Are there distributed sources of suprathermal particles in the solar wind? What is the relative importance of spatial and temporal variability in the structure of the solar wind at 1 AU?

Numerous theories and observational studies link turbulence to heating, acceleration of the wind, and energetic particle transport, yet baseline theoretical descriptions are not fully agreed upon. This disconnect inhibits progress in understanding basic features of the heliosphere, such as the evolution and the nature of the heliospheric magnetic structure. This FST would enable phenomenology from observations and simulations to confront state of the art theoretical frameworks, with the goals of identifying levels of agreement as well as areas where theoretical advances or modifications are needed. The knowledge gaps to be addressed include, but are not limited to, any identified disconnects between the observations of the above phenomena and the basic theory intended to describe them. This FST is made timely by the new data from observatories such as PSP, SolO, DKIST, and PUNCH.

Overview of Science Goals:

The goal of this FST is to develop a more thorough understanding of time-dependent processes in the solar wind through the combination of data analysis, theory, and modeling. Proposing teams can describe a focused effort that addresses one or more relevant components of this topic; however, they should discuss how their effort would contribute to the overall goals of the FST and the degree to which they would be willing to support the overall team's goals, in addition to their specific scientific objectives. To address this, in addition to data-centric, model-centric, or theory-centric investigations, more holistic investigations aimed at merging the anticipated individual teams into a coherent group should also be considered.

The potential user communities for such studies range from basic space plasma physics, to global solar wind modelers, to users of energetic particle transport models (from space weather modelers to outer heliosphere observers and astrophysicists).

Measures of success could include providing critical assessments of competing physical processes for the creation and evolution of the solar wind out to 1 AU.

Applicability to LWS within NASA Heliophysics:

This FST will advance the understanding of the physical mechanisms producing the solar wind and the regions of the Sun producing the solar wind and directly applies to a broad span of LWS Strategic Science Areas (I, II, III, IV, VIII, IX).

This FST supports three Key Science Goals of the 2013 Decadal Survey: #1 “Determine the origins of the Sun’s activity and predict the variations in the space environment,” #3 “Determine the interaction of the Sun with the solar system and the interstellar medium,” and #4 “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.”

Envisioned Focused Science Topic Implementation Strategy:

This FST should utilize all relevant in situ spacecraft measurements in the inner heliosphere, particularly PSP and SolO. All pertinent solar-imaging observations should be utilized, potentially with particular emphasis on DKIST and PUNCH. Large-scale and microscale computer simulations should be employed in collaboration with data analysis.

Types of investigations could include:

- Innovative statistical data analysis.
- Radial-line-up intervals of in situ measurements; particularly important is the need to determine how to line PSP observations up with observations at 1 AU.
- Studies in which two or more competing theories could be judged with simulations and data.
- System-science and machine-learning approaches to multiple data sets.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Note to NASA:

This FST is a merger of 186 and 188 with task ideas taken from 181 (machine learning) and 191 (working to determine how to line-up PSP observations with 1 AU observations).

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FST.15 Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle

Magnetized plasma escapes from the rotating, time-dependent Sun and forms the solar wind, which propagates outward across the solar system filling the entire heliosphere. Across this long journey the physical conditions encountered vary greatly. From the corona to the solar wind, the plasma transitions from subsonic to supersonic. In the inner heliosphere, the solar-wind plasma contains large amplitude Alfvénic fluctuations that taper off with distance. The Sun emits plasma with a range of speeds, and these parcels (with differing speeds) dynamically interact with one another forming large-scale outward propagating compressions and rarefactions.

To understand the solar wind throughout the heliosphere, a large number of physical processes under a variety of conditions must be understood, under variable solar driving with very large time lags. These dynamic interactions within the solar wind plasma steepen to form shocks between 1 to 4 AU, and those shocks eventually taper off. On small scales, there is solar wind turbulence that evolves with distance. The amplitude of solar wind structures and the variability of the solar wind is significantly reduced between 4 and 10 AU. Beginning around 4 to 5 AU, the energy of interstellar pickup ions becomes important, and between 20 and 30 AU, the interaction of the solar wind with the interstellar pickup ions reduces the solar-wind speed and heats the solar-wind plasma. Shocks are modified by the interstellar pickup ions. Eventually, as the interstellar pickup ions become more important, the solar wind becomes subsonic at a termination shock (80-100 AU) and continues to interact with the interstellar medium until reaching the outer heliosphere boundaries. The solar wind plasma takes a fraction of a solar cycle to travel from the Sun to the outer boundary, and the nature of the Sun's driving of the heliosphere varies with time.

Long duration, high quality measurements are essential for quantifying the solar cycle and its impacts on the heliosphere. Systematic measurements of the solar photospheric magnetic field are available for more than four cycles (e.g., KPVT, MDI, HMI); extreme ultraviolet (EUV) measurements of the solar corona for two cycles (e.g., EIT, Hinode, AIA, STEREO); X-ray observations of the solar corona for 3 cycles (e.g. YOHKOH, GOES, Hinode); and coronagraph images have been made for two cycles (LASCO). Multiple in situ observatories (e.g., ACE, Wind, STEREO) have been in operation for 2 solar cycles. Ulysses provides out-of-ecliptic coverage for nearly 2 solar cycles. Combined with OMNI, these measurements provide a long and invaluable baseline from which inferences about the Sun's variability, solar wind generation, and transient events as a function of solar cycle can be drawn. These long-duration inner-heliosphere observations (e.g., 1 AU and MAVEN) can be combined with data from outer heliosphere missions (e.g. New Horizons and Juno) to characterize how the heliosphere's global structure evolves. Remote observations of large-scale processes, also applicable to other heliospheres (e.g. IBEX and IMAP), could be advantageously incorporated. Parker Solar Probe is on a journey to cross the Alfvén point and study the solar wind's sub- to supersonic transition in situ. Solar Orbiter will provide high-resolution inner-heliosphere observations. This collection provides an unparalleled opportunity to characterize the mechanisms that govern the plasma and magnetic environment of the slowly varying heliosphere.

Overview of Science Goals:

This FST has two coupled goals. (1) Understanding the physical processes behind the formation and propagation of solar-wind structures throughout the heliosphere and variability with the solar cycle. (2) Understand how the solar magnetic field and coronal structure determine the plasma and magnetic-field conditions in the inner heliosphere as the solar cycle waxes and wanes?

Objectives underlying these goals include: (1) Utilization of long-term measurements to quantify how the solar cycle impacts the in situ plasma and magnetic field of the inner heliosphere; (2) Understanding the radial evolution of wave activity, turbulence, dynamic interactions, and shock formation; (3) Understanding how multiple solar wind structures (slow and fast streams and CMEs) merge to form Merged Interaction Regions (MIRs) and Global Merged Interaction regions (GMIRs); and (4) Understanding how the solar wind and interstellar pickup ions interact to modify shocks in the outer heliosphere and form both the heliosheath and heliopause boundaries.

Applicability to LWS within NASA Heliophysics:

This FST addresses a broad span of LWS Strategic Science Areas (I, II, III, IV, VIII, IX), focusing on physics-based understanding of the evolution of the solar wind throughout the heliosphere and the physical processes that govern that evolution.

This FST supports three Key Science Goals of the 2013 Decadal Survey: #1 “Determine the origins of the Sun’s activity and predict the variations in the space environment,” #3 “Determine the interaction of the Sun with the solar system and the interstellar medium,” and #4 “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.”

Envisioned Focused Science Topic Implementation Strategy:

Gaining an understanding of the heliosphere wherein a large number of physical processes under a variety of conditions act, under variable solar driving with very large time lags, will require a holistic approach.

Types of investigations could include:

- Utilize long-term measurements to quantify how the solar cycle impacts in situ plasma, magnetic field, and energetic particle observations.
- Connect these diverse observations to models.
- Create homogeneous datasets that combine multiple instruments into super-instrument spanning multiple cycles of observations.
- Apply machine-learning techniques to tie together diverse large data sets and to build empirical models of the heliosphere.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Note to NASA:

This FST is a merger of 194 and 195 with task ideas taken from 181 (machine learning).

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FST.16 Solar Flare Energetic Particles and Their Effects in Large Solar Energetic Particle Events

A key component of the LWS program is to understand energetic particles accelerated during solar eruptive events. Solar energetic particles (SEPs) that are accelerated at shocks driven by flares and coronal mass ejections (CMEs) have been identified as a key element of space weather. These particles can increase high-energy emissions, such as X-rays and gamma-rays that ionize the thermosphere and ionosphere, by serving as 'seed' particles for subsequent reacceleration by shocks and by escaping into the corona and interplanetary (IP) space. The component that escapes into space contains energetic electrons, protons, and minor components such as 3He, heavy, and ultra-heavy ions.

The flare accelerated particles often have compositions anomalously different from that in the solar corona and solar wind, indicating a distinct acceleration process from the traditional shock acceleration. Solar flare particles are thought to contribute to large SEP events, by providing pre-accelerated suprathermal particles. The numbers, energy spectrum, and lifetimes of these particles are not well understood. Particle acceleration in solar flares is an outstanding problem with several science objectives that need to be addressed to further understand the associated space weather effects.

In addition, particle acceleration in stellar flares is a ubiquitous process in the universe. Our Sun provides a unique opportunity to study energetic particles and their source flares jointly and to apply that understanding to other stellar systems. The planetary habitability within those extra-solar systems is directly impacted by their energetic particle environments.

Overview of Science Goals:

The science goal of this FST is to understand solar flare accelerated particles, including protons, electrons, 3He, and heavier ions, and their effects on large SEP events. More specifically, the objectives are to study the production and transport of flare particles in the flare region, the escape and propagation of the particles in the coronal and IP space, and their contribution to SEP events.

Some key science questions include:

1. Elemental Composition: What causes anomalous elemental composition that is markedly different from the solar corona or solar wind? Is the composition due to acceleration mechanism, or do ambient conditions (including plasma composition, temperature, density) play an essential role? Is the anomalous composition an inherent feature of ion acceleration in all flares as suggested by gamma-ray line observation
2. Injection and Propagation: What is the role of coronal/IP propagation from a solar flare to 1 AU on energetic particle properties? How do flare particles propagate out of the acceleration region and how do they contribute to large SEP events?
3. Ions and Electrons Relation: How much of the total energy content is redistributed to ion and electron acceleration? How interrelated are the electron and ion acceleration mechanisms in solar flares? What is the relationship between heating and acceleration of suprathermal particles?

Measures of success could include:

- Creation of one or more theoretical models for explaining the observations of anomalous composition of 3He, heavy ions and ultra-heavy nuclei.
- Development of comprehensive models and observations for detailed understanding of propagation of flare particles from the Sun to 1 AU.

- Development of an understanding of how flare particles propagate out of the acceleration region and contribute to large SEP events, either as 'seed' particles or a component of the SEP population
- Development of an understanding of how magnetic energy is converted and distributed into electrons and ions and how the energy is partitioned into heating and nonthermal acceleration.

Applicability to LWS within NASA Heliophysics:

This FST addresses a broad span of LWS Strategic Science Areas (I, II, III, VIII), focusing on physics-based understanding of the origins, variability, and space weather impacts of solar energetic particles.

The FST responds directly to two of the high-level science goals from the Heliophysics Decadal survey: (1) Determine the origins of the Sun's activity and predict the variations in the space environment, and (4) Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. Furthermore, the FST is highly relevant to two LWS Science Strategic Goals: (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, and (2) Deliver the understanding of how and to what degree variations in the solar radiative and particulate output contribute to changes in global and regional climate over a wide range of time scales.

Envisioned Focused Science Topic Implementation Strategy:

This FST should use relevant spacecraft and ground-based measurements for energetic particles, such as those from Parker Solar Probe and Solar Orbiter as well as archived flare and multi-spacecraft data. Theoretical modeling and numerical simulations are important for further understanding the acceleration and propagation of solar flare particles. The use of Artificial Intelligence (AI) and Machine Learning (ML) are encouraged (but not required) in this FST.

Types of investigations could include:

- Develop a theoretical and observational understanding of anomalous energetic ion composition in solar flare particles.
- Develop models and observations for release of solar flare particles in the corona and propagation in the IP space.
- Develop modeling and observational understanding on the roles of solar flares in producing large SEP events.
- Develop observations and theories for ion acceleration and electron acceleration and their relation.

Implementation strategies could include data analysis, data model comparison, database development, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a combination of community inputs 181, 188, and 193.

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FST.17 Understanding the Transport Processes of Solar Energetic Particles from Their Origins to the Entire Inner Heliosphere

Solar energetic particle (SEP) observations at Earth's orbit include a mixture of different physical processes, making it challenging to pin down the exact role of individual processes. Because of this ambiguity, a comprehensive understanding of the underlying physical mechanisms of SEP events from their origins to the entire heliosphere is still lacking. With the launch and continuous observations made by Parker Solar Probe (PSP) and Solar Orbiter (SolO), the unprecedented latitudinal/longitudinal/radial coverage of inner heliosphere observations offers great opportunities to examine the transport mechanisms and effects of SEP events.

In addition, various heliospheric plasma and magnetic structures, such as coronal mass ejections (CMEs), corotating interaction regions (CIRs), magnetic clouds (MCs), and heliospheric current sheets (HCSs), may cause significant variabilities in SEP properties (energy spectra, particle composition, temporal evolution, etc.) at different locations in the inner heliosphere. This FST calls for detailed studies on SEP transport processes due to magnetic connectivity, solar wind turbulence, and heliospheric structures, and new data to model comparisons to improve predictions of SEP properties at any location within the inner heliosphere.

This FST addresses the following questions:

1. What propagation factors control the observed SEP properties, such as intensity, energy spectra, composition, and temporal evolution?
2. How is the SEP event evolution influenced by interplanetary transport, magnetic connectivity, and heliospheric structures?
3. What is the relative importance of the various transport processes on the SEP properties measured at different latitudinal, longitudinal, and radial locations and at different energies?

The goals of this topic are timely because of the unprecedented observations from PSP and SolO, in company with other ongoing SEP measurements, which will offer new insight on the acceleration and transport of SEPs. A clearer understanding of the SEP events would improve the current SEP forecast capability, which is crucial to mitigate the radiation risk in future space exploration. This FST will lead to new data analysis and models for energetic particle transport that constrains other aspects of SEP events.

Overview of Science Goals:

The goal of this FST is to disentangle and evaluate different processes in the transport of energetic particles in the inner heliosphere by utilizing new observations, data analysis, and energetic particle modeling. This goal is important for improving current forecast models of SEP events. With the successful launch and operation of PSP and SolO, their unique observations will be essential for achieving this goal.

Measure of success could include:

- Demonstration of a capability to quantitatively describe individual SEP events using multiple spacecraft observations and to derive and distinguish different transport effects.
- Addition of numerical modeling and theoretical studies for studying and distinguishing different particle transport processes and evaluation of their relative importance.

- Demonstration of agreements between model predictions and observations for SEP events.

Applicability to LWS within NASA Heliophysics:

This FST addresses two of the LWS Strategic Science Areas (III, VIII), focusing on a physics-based understanding of energetic particle transport in the inner heliosphere.

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

Envisioned Focused Science Topic Implementation Strategy:

A team complement of observational and theoretical researchers is needed to make substantial progress on this topic. Available data sources for this FST include spacecraft data at 1 AU and closer to the Sun (e.g., PSP, SolO, ACE, GOES, Wind, etc). Modeling methods appropriate for addressing this topic include particle transport models for predicting the propagation of energetic particles from the Sun to points of interest in the inner heliosphere. In addition, new theories on energetic particles in magnetic turbulence should be encouraged. This FST has the goal of improving the theoretical modeling of energetic particle transport in the coronal magnetic field and solar wind turbulence. The use of Artificial Intelligence (AI) and Machine Learning (ML) are encouraged (but not required) in this FST.

Types of investigations could include:

- Study the propagation and distribution of SEPs using multiple spacecraft observations.
- Observation-model comparison for understanding and constraining transport properties such as adiabatic cooling as well as parallel and perpendicular diffusion of energetic particles in the solar wind turbulence.
- Theoretical studies and model development for particle transport in the solar wind turbulence.
- Study effects of heliospheric structures (CMEs, HCSs, MCs, and CIRs) on the transport of energetic particles.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is developed from community inputs 181, 188, and 199. Removed some vague ideas on SEP acceleration and made it focus on the transport process.

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FST.18 Extreme Solar Events — Probabilistic Forecasting and Physical Understanding

Extreme solar events, defined as events with physical properties at or beyond the upper quartile of their distributions, introduce significant potential hazards associated with abrupt increases in solar energetic particle radiation and geospace superstorms. Rarely occurring extreme solar events generate intense X-rays and solar radio bursts, accelerate solar energetic particles to relativistic velocities within minutes, and cause powerful coronal mass ejections. In particular, extreme solar radio bursts are recognized as key, yet poorly understood, indicators and probes of the underlying physical processes of such events, and critical observables of these bursts have only just become accessible through recent advances in radio instrumentation.

At Earth, the associated changes in the space environment can cause detrimental effects to the electricity distribution grid. In space, extreme solar events can damage satellites and avionics and pose a hazard to space travelers. Extreme solar events also cause increases in radiation levels at aviation altitudes that can affect airline passengers and crews. Additional effects of extreme events include disruptions of satellite navigation systems, mobile telephones, and a host of additional effects for Earth (including ozone destruction) and satellite-based technologies. Extreme solar events have consequently been identified as a risk to the world economy and society.

Several examples of extreme solar event effects include the 1989 collapse of part of the Canadian electricity grid. A superstorm which occurred in 1859, now referred to as the “Carrington event”, is the largest for which we have measurements; and even in this case the measurements are limited to perturbations of the geomagnetic field. An event in 1956 is the highest recorded for atmospheric radiation. The events of August 1972, October 1989 and October 2003 were associated with the highest recorded levels of solar energetic particle radiation measured on spacecraft. Important questions such as how often solar superstorms occur, what their probabilities are, how they are generated, and whether the events listed above are representative of the long-term risk remain unanswered. This FST calls for a concerted effort to study extreme solar events observationally, theoretically, and with simulations to identify potential causes and possible precursors of these events with an emphasis on development of the physical understanding that may be used for probabilistic forecasting. Since extreme solar events are rare, studies of moderate to large storm events will be important for developing the physical understanding necessary for predicting the behavior of extreme events.

Overview of Science Goals:

The goals of this FST are twofold: to develop models of extreme solar events, and to test these models via comparison against diverse satellite and ground-based datasets of moderate to large solar events and historic extreme solar event data from sources such as ice cores and tree rings. Measures of success are: the development of metrics to test or quantify the success of extreme solar event models; the development of observational precursors that can be used to quantify potential development of extreme solar events and associated geoeffectiveness; the development of methodologies for probabilistic forecasting of extreme solar events (e.g., per source region, per cycle, and across the historical record); the examination of historic datasets that can be used to assess extreme events that may have occurred in the past.

The driving motivation of this FST is to advance substantially our physical understanding of extreme solar events, to identify observational precursors, and to develop an understanding of the probabilities that such events will arise in the future. Proposals to this FST should demonstrate how the expected advances will be relevant to user needs (for example, NASA/SRAG or NOAA/SWPC). Individual proposals should identify how they will contribute to the FST and aid with development to enable predictive understanding, observationally based forecasting, and probabilistic understanding.

Applicability to LWS within NASA Heliophysics:

This FST addresses a broad span of LWS Strategic Science Areas (I, II, III, IV, VIII), focusing on enabling forecast capabilities for the events driven by the variability of solar magnetic fields and the subsequent impacts on the heliosphere.

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

Envisioned Focused Science Topic Implementation Strategy:

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

Implementation strategies could include data analysis, data model comparison, database development, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is merger of roll-over 170 with three supporting comments from the community encouraging continued FST inclusion and enhancement with extreme radio burst studies due to new instrumentation and long term forecasting.

There is an ongoing Extreme FST Team that was solicited 2017 or 2018 entitled “Understanding Physical Processes in the Magnetosphere–Ionosphere / Thermosphere / Mesosphere System during Extreme Events”; however, that one focuses on the impacts at earth rather than the sources and forecasting. Both aspects are key and require different types of studies, models, and data implementation.

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FST.19 Towards a Quantitative Description of the Magnetic Origins of the Corona and Inner Heliosphere

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

However, a number of issues make it difficult to use these various data to their fullest extent. For instance, difficult-to-correct zero-point offsets in magnetograms mean that measurements often differ substantially from one instrument to the next, making it difficult to generate global maps of the Sun. The fields in the polar regions are poorly observed, and line-of-sight (LOS) magnetograms (rather than the potentially available vector measurements) are often used to reconstruct the radial photospheric field. The evolution of the magnetic field and plasma from the surface through the corona is not well understood, leading to the use of empirical approaches to describe coronal heating and acceleration. Finally, current models do not take full advantage of key information on the magnetic field provided indirectly by multi-viewpoint coronagraph observations or directly by multi-point in situ measurements in the inner heliosphere. These issues result in a research 'bottleneck' that hinders the reliability of global coronal models, which in turn drive the heliospheric models used to provide predictions of the heliospheric state.

In addition to large-scale global phenomena, the photosphere is the source of vital small scale magnetic flux elements that drive and propagate sub-arcsecond dynamics. Bridging the gap between the global magnetographs mentioned above and high-resolution photospheric observations from instruments such as Hinode/SOT, IRIS, DKIST, and Solar Orbiter is critical to improving the physical understanding underlying subgrid-scale models.

This is a timely topic, considering that the Parker Solar Probe mission is now measuring and observing the solar wind near its source region and the Solar Orbiter, DKIST, and PUNCH observatories will be fully operational in the near future. A full understanding of these measurements requires accurate coronal and heliospheric models of the magnetic field.

Overview of Science Goals:

The primary goal of this FST is to obtain a quantitative understanding of magnetic field structure from the photosphere to the inner heliosphere. To address this goal, proposed investigations should include one or more of the following objectives: 1) Understand how plasma processes or time-dependent evolution lead to global non-potentiality; 2) Understand how magnetic connectivity evolves from the photosphere to the inner heliosphere; 3) Understand how the magnetic field drives coronal and heliospheric structure and dynamics.

Measures of success could include:

- Demonstration of an understanding of the magnetic connectivity to Earth, Mars, Moon and other points in the inner heliosphere.

- Improved modeling of the corona below the Alfvenic point.
- Production of time sequences of global maps that smoothly assimilate new data (including far-side measurements) and are made available to drive global models (research and operational) to provide a real-time forecast of the state of the heliosphere.

The successful outcome of this FST will improve, if not remove, an important obstacle in our ability to predict the state of the inner heliosphere. The results will impact across a wide swath of the user community, including space exploration and satellite operations.

Applicability to LWS within NASA Heliophysics:

This FST addresses a broad span of LWS Strategic Science Areas (I, II, IV, VIII, X), focusing on enabling a physics-based understanding of the global solar magnetic field.

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

Envisioned Focused Science Topic Implementation Strategy:

The surface field influences coronal hole boundaries, the solar wind, and the interplanetary magnetic field, but this relation is not one-to-one. Studies linking coronal and heliospheric structure to surface field distributions would synergize well with the data-oriented projects outlined in this FST. Theoretical, numerical, and data analysis methods are required to address this topic's science goal and objectives.

Types of Investigations could include:

- Develop methodologies to improve the cross-calibration of magnetic field measurements from different telescopes.
- Develop methodologies for accounting for poorly observed polar field contributions and far-side field contributions.
- Bi-directional research pathways to explore, for example, how coronal or solar wind models and observations may be used to improve and inform surface-field maps when data is not available or uncertain (e.g., at the poles).
- Studies that explore novel or little-used data (e.g., chromospheric or coronal magnetic fields from optical/infrared or radio techniques), advanced inversion algorithms (e.g. non force-free approaches), machine learning approaches, and data assimilation techniques.
- Physics-based and statistical studies connecting surface-field distributions to coronal and heliospheric structure.

- Development of methods for the 3D magnetic field reconstruction using multi-viewpoint photospheric magnetograms and EUV observations.
- Development of techniques for incorporating vector magnetic fields, in addition to fields derived from LOS observations, into radial field maps.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 173 with three supportive community comments.

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FST.20 Understand Energy Partition and Energy Release Processes in Eruptive Events

Coronal mass ejections (CMEs) are one of the major manifestations of space weather and constitute one of the major hazards posed by solar activity. One of the overarching goals of the LWS program is to predict their occurrence and geo-effectiveness. The latter is critically influenced by the amount of energy released in the eruption process to heat and accelerate CME plasmas, by the conditions of the solar corona and interplanetary space that the CME faces once launched, and by the CME's own magnetic field orientation.

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

Overview of Science Goals:

The goal of this FST is to understand how the magnetic energy that drives all eruptions is distributed among the various eruptive components (CMEs, flares, heating, kinetics, and particles). To address this goal, proposed investigations should include one or more of the following objectives: 1) Determine how the energy released during the CME process is distributed among the various energy terms; 2) Understand if and how such partition changes in different CME events and how it affects their geo-effective potential; 3) Understand how the released magnetic energy drives CME kinematics and dynamics in the corona and inner heliosphere.

Measures of success could include:

- Demonstration of an understanding of the energy budget distribution in explosive events and the sources of its variability across the observed spectrum of CME events.
- Demonstration of an increased ability of CME eruption models to successfully reproduce the array of different observables produced by the fleet of NASA space missions.
- Understanding of how the CME energetics influence the coronal and inner heliospheric evolution of CMEs, shocks, and SEPs.

The successful completion of this FST will provide improved CME eruption models, along with improved understanding of the evolution of CME, shocks, and SEPs in the corona and inner heliosphere. These products will be of maximum relevance to the space weather forecast community.

Applicability to LWS within NASA Heliophysics:

This FST addresses a broad span of LWS Strategic Science Areas (I, II, III, IV), focusing on a physics-based understanding of CME energy partition.

This topic also addresses two Key Science Goals (KSG) of the Heliophysics Decadal Survey; namely, KSG 1 (“Determine the origins of the Sun’s activity and predict the variations of the space environment”) and KSG 4 (“Discover and characterize fundamental processes that occur both within the Heliosphere and throughout the Universe”).

Envisioned Focused Science Topic Implementation Strategy:

This FST specifically encourages, when available, the use of spectrally resolved observations, and the prediction of spectroscopic observables, for model validation. A plethora of data sources are, or will be available in the near future, to meet this need. Theoretical, numerical, and data analysis approaches along with simulations, data-model comparisons, and the development of tools and analysis techniques will be required to address the FST’s science objectives.

Types of investigations could include:

- Develop data-driven, data-constrained, data-inspired, or idealized models of CME eruptions and predictions of the energetics of the plasma for all CME components;
- Compile statistical studies of CME energetics and related activity, such as flares, shocks or SEPs;
- Develop methodologies to improve estimates of energetics in eruptive flares, particularly between accelerated particles and radiative components;
- Develop methodologies for improved 3D kinematic measurements of CME components (e.g., shock, internal structures) in the corona and inner heliosphere;
- Improved CME heating models by assessing model performance through detailed comparison between predicted and observed narrow band and spectrally resolved emission from the fleet of NASA space observatories.
- Synergistic studies between remote sensing and in situ observations of CMEs in the inner heliosphere to improve CME observations and models;

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of roll-over 175 with merging the 4 supportive comments.

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FST.21 Atmospheric Evolution and Loss to Space in the Presence of a Star

The overarching goal of this FST is to explore the atmospheric loss and evolution of a planet's atmosphere (including Earth) through its interactions with the Sun. In order to achieve this goal, the investigation of various plasma processes that lead to atmospheric loss in both unmagnetized and magnetized planets is rendered necessary. Comparing and contrasting the processes that lead to atmospheric loss from planets with strong, weak, or null magnetic fields could potentially reveal the planetary conditions under which magnetospheric and ionospheric processes dominate over other processes that can result in the loss of planetary atmospheres.

The presence of an atmosphere is presumed to be one of the fundamental criteria for sustaining a habitable environment. However, atmospheric escape remains an extremely complex problem, and despite the wealth of measurements from Earth, Mars, and Venus, we lack a comprehensive understanding of the critical factors that regulate the ultimate loss of an atmosphere to space. The Goldilocks analogy of Venus possessing an overly thick atmosphere, Mars having too little, and Earth featuring the "optimal" amount is not clearly understood, from the epoch of planetary formation to future evolution. For example, one question that has been intensively debated over the years is: does a magnetic field inhibit or amplify atmospheric loss? 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 of 10^{24} to 10^{26} particles per second, chiefly due to the intricate ionospheric and magnetospheric processes and pathways for ultimate escape.

Given the wealth of data from Earth (Cluster, MMS, and many more), Mars (Mars Express, MAVEN, ExoMars Orbiter), Venus (PVO, Venus Express), Titan (Cassini), Pluto (New Horizons), and the upcoming missions of Mars 2020 and ExoMars 2022 Rover, it is timely to seek a quantitative assessment of our current understanding of atmospheric loss and the factors that control it, both from an experimental viewpoint and a theoretical one.

Overview of Science Goals:

Key science goals of this FST include: 1) Determining how planetary atmospheres were lost, as well as the channels through which this depletion occurred, 2) Understanding the effects of solar cycle and seasonal variations as well as solar evolution on the escape rates of their atmospheres, and 3) Investigating the impact of atmospheric composition and the presence of magnetic fields on atmospheric retention.

Measures of success could include:

- Capability to assess the significance of atmospheric compositions and magnetic fields for atmospheric losses.
- Capability to assess the impact of solar cycle and seasonal variations on atmospheric losses.
- Capability to assess the significance of the solar wind and solar activity (e.g., CMEs, CIRs and SEPs), interplanetary magnetic field, and other processes on atmospheric losses.
- Capability to assess the roles of solar evolution on integrated atmospheric losses through time, long-term climate evolution, and planetary habitability.

Applicability to LWS within NASA Heliophysics:

This FST topic falls under the “Sun-Planet and Star-Exoplanet Connections” thrust of “Future Opportunities and Challenges” of the LWS 10-year vision and directly addresses a broad span of LWS Strategic Science Areas (I, II, IX, X), focusing on understanding atmospheric variability due to stellar dynamics.

The topic addresses Key Science Goals from the Heliophysics Decadal Survey: 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; Deliver the understanding of how and to what degree variations in the solar radiative and particulate output contribute to changes in global and regional climate over a wide range of time scales; and Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

This FST is relevant to the following Decadal Science Challenges concerning Solar Wind-Magnetosphere Interactions (SWMI): 3) Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind; and 4) Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems.

Envisioned Focused Science Topic Implementation Strategy:

This FST can leverage current solar, magnetospheric, and ionospheric models of the Earth, Mars, and other planets within our solar system to aid in developing sophisticated multidimensional multi-fluid models that can be applied to study atmospheric losses from terrestrial planets around the Sun over time.

Types of investigations could include:

- Investigations of atmospheric losses from both unmagnetized and magnetized planets (with different sizes and atmospheric compositions) based on analyses of observational datasets from multiple missions that have visited planets with varying levels of magnetic field strength (a few examples of such missions are mentioned in the introduction above).
- Utilization of the existing heliophysics models (i.e., solar models and coupled planetary magnetosphere-ionosphere-atmosphere models) to investigate atmospheric losses from both unmagnetized and magnetized planets of different sizes and atmospheric compositions.
- Extrapolation and application of spacecraft observations to the early solar system for comprehending how an active young Sun impacted both unmagnetized and magnetized planets of different sizes and atmospheric compositions.
- Development of solar and planetary models that can be applied to the early solar system to assess how an active young Sun impacted both unmagnetized and magnetized planets of different sizes and atmospheric compositions.

Implementation strategies could include data analysis, data model comparison, simulations, theory and model development, and tools and analyses techniques.

Notes to NASA:

This FST is a merger of 178 (roll-over) and community input 180 (plus new comments) and focuses on planets (including Earth) in the solar system.

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FST.22 Stellar Impact and Extreme Activity on Exoplanetary Atmospheric Loss and Habitability

Recent missions such as Kepler and TESS have detected many extrasolar systems with confirmed planets. They have also revealed that the host stars, like our Sun, may produce “superflares” and coronal mass ejections (CMEs) that could induce severe extrasolar space weather (xSpW) events, thus instigating planetary atmospheric escape and limiting planetary habitability. This process is especially true for exoplanets residing in the close-in habitable zones (HZs) of low mass stars, where climate modeling (chiefly based on stellar radiation) suggests that liquid water may exist on a planetary surface. This conclusion largely neglects the impact of the stellar wind and stellar magnetic activity on the erosion of an exoplanet’s atmosphere. In general, low mass stars (e.g., M dwarfs) are more magnetically active than solar-type stars. However, occurrence rates of flares/CMEs on solar-type stars are significantly higher when they are young.

Understanding the myriad impacts of stellar winds and activity on exoplanetary atmospheric retention through the coupling between the thermosphere/ionosphere and magnetosphere is timely given the increasing number of Earth-like exoplanets discovered in the traditional HZs of M dwarfs. Stellar activity such as CMEs, in particular, can significantly enhance atmospheric ion escape rates. The eruptions from low mass stars are magnetic in nature and so are solar eruptions. Hence, solar studies provide a unique, if not the only, means of understanding xSpW. Solar eruptions are being modeled in great detail thanks to recent advances in observational facilities and numerical modeling. The existent solar and planetary ionosphere/thermosphere/ magnetosphere models have already been used to probe the consequences of severe space weather in extrasolar systems, such as resultant atmospheric losses from exoplanets around M dwarfs, which is of paramount importance for determining planetary habitability.

The history of the solar system is witnessing a repeat of sorts when it comes to the younger exoplanet systems. Studying these stellar-exoplanet systems will offer us valuable lessons regarding the evolutionary history of our own solar system, thus aiding us in understanding how Earth and other terrestrial planets (such as Mars and Venus) responded to a much more active young Sun. On this note, state-of-the-art models of the Sun/solar wind, Earth/planetary atmospheres (including ionospheres/thermospheres), and magnetospheres can be greatly leveraged by extending their applicability to a much wider range of stellar and planetary parameters. This FST offers a great opportunity for connecting the heliophysics community to the rapidly developing field of exoplanetary research and the search for habitable environments.

Overview of Science Goals:

Key science goals of this FST include 1) Understanding the physical origin of stellar winds and eruptions from stars of different ages and/or types, 2) Assessing the impact of highly intense stellar radiation and stellar winds (from M-dwarfs or young Sun-like stars) on exoplanetary atmospheric losses and habitability, 3) Understanding the planetary responses to extreme space weather events such as superflares and CMEs that have much higher energy compared to those observed from the current Sun, and 4) Defining the expected observational signatures of space weather, both at the locations of the planet and star, and the ensuing consequences for planetary atmospheric retention.

Applicability to LWS within NASA Heliophysics:

This FST addresses a broad span of LWS Strategic Science Areas (I, II, IX, X), focusing on the understanding of the stellar impact and extreme activity on exoplanetary atmospheric losses and habitability that will be of specific benefit to both Heliophysics and Astrophysics communities.

From the LWS perspective, we will understand more about the solar-stellar connection, the Sun in time (from comparisons with young stars), how magnetized and unmagnetized planets respond to extreme space weather events when the stars are much more magnetically active relative to the current Sun, and the capacity of existing heliophysics models to study these phenomena. A key component of this FST is the atmosphere–ionosphere–magnetosphere coupling, an area that addresses areas of Heliophysics Decadal Science Challenges "Solar Wind-Magnetosphere Interactions" (SWMI) and "Atmosphere-Ionosphere-Magnetosphere Interactions" (AIMI). It will critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations drawn from different magnetospheric systems. It also addresses the finding by the LWS Steering Committee (LWS 10 Year Vision Report, page 2): a need for "a joint Heliophysics and Astrophysics program to investigate the effects of stellar variability on astrospheres and the exoplanets within them". Moreover, it addresses the following Heliophysics Decadal Survey goals: Determine the origins of the Sun's activity and predict the variations in the space environment; Determine the interaction of the Sun with the Solar System and the interstellar medium; Discover and characterize fundamental processes that occur both within the heliosphere and throughout the Universe.

Envisioned Focused Science Topic Implementation Strategy:

This FST has the potential to leverage current solar, magnetospheric, and ionospheric models of the Earth, Mars, Venus, and other planets, for the purposes of developing sophisticated multidimensional multi-fluid models of stellar winds, CMEs, and co-rotating interaction regions (CIRs) that incorporate coupled stellar-wind–magnetosphere and ionosphere–thermosphere– mesosphere systems corresponding to different kinds of rocky bodies around stars of different ages and/or types.

Types of investigations could include:

- Development of modeling approaches to extend solar wind and CME models to stellar conditions based on inputs from stellar observations (e.g., stellar radiation, magnetic fields, and flares).

- Development of modeling approaches to extend the planetary ionosphere/thermosphere and magnetosphere models to exoplanets (with different magnetic field strengths, sizes, and atmospheric compositions) that may experience much severer stellar environments.

- Investigations of stellar impacts (including stellar radiation, stellar winds, and extreme extrasolar space weather events) on exoplanetary atmospheres (including thermospheres and ionospheres) and magnetospheres.

- Investigations the connection between stellar modeling results and current and future stellar observations (e.g., detection of CMEs).

- Investigations of the connection between the exoplanetary modeling results and current and future observations of planetary atmospheres and magnetic fields.

Implementation strategies could include data analysis, data model comparison, simulations, and theory and model development.

Notes to NASA:

This FST is a merger of roll-over 178 and community inputs 189 and 192. It focuses on space weather and exoplanets beyond the solar system.

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7 Appendix

This Appendix provides the cross-reference numbers to identify which of the 2020 Community Inputs were used in the development of the individual FSTs (see notes to NASA at end of each FST).

165	2018 FST-Understanding the Impact of Thermospheric Structure and Dynamics on Orbital Drag
166	2018 FST-Pathways of Cold Plasma through the Magnetosphere
167	2018 FST-Understanding the Variability of the ITM System Due to Tides, Planetary Waves, Gravity Waves, and Traveling Ionospheric Disturbances
168	2018 FST-Connecting Thermospheric Composition and Space Weather
169	2018 FST-Understanding Ionospheric Conductivity and its Variability
170	2018 FST-Extreme Solar Events — Probabilistic Forecasting and Physical Understanding
171	2018 FST-Connecting Auroral Phenomena with Magnetospheric Phenomena
172	2018 FST-Understanding SpaceWeather Effects and Developing Mitigation Strategies for Human Deep Space Flight
173	2018 FST-Solar Photospheric Magnetic Fields
174	2018 FST-Coupling of Solar Wind Plasma and Energy into the Geospace System
175	2018 FST-Combining Models and Observations to Study CME Plasma Energetics in the Inner Corona
178	2018 FST-Atmospheric Evolution and Loss to Space in the Presence of a Star
180	The Effects of Solar Cycle Variations on Atmospheric Evolution and Escape of Terrestrial and Habitable Planets
181	Applications of machine learning for physics discovery in the heliosphere
182	Space Weather at the Moon: Alfvenic Plasma Flows, Plasmoids and Magnetospheric - Solar Energetic Particles
183	Influence of multi-scale high-latitude forcing on mid- and low-latitude perturbations
184	Auroral Region Drivers of the Ionosphere-Thermosphere System
185	Synergistic view of the global magnetosphere
186	Understanding the Time-Dependent Ambient Solar Wind
187	Closing the Gap between Coronal and Heliospheric Evolution of Coronal Mass Ejections
188	Connecting turbulence, heating, and energetic particles: phenomenology and underlying physics
189	The Magnetic Origin of Space Weather Around Sun-like Stars
190	Knowledge gap to be filled: The Source of the Discrepancies Between Heliospheric Model Simulations and Observations at 1 AU
191	Tracking and Evolution of Heliospheric Structures
192	Extreme activity and exoplanet habitability
193	Solar Flare Energetic Particles and their Effects on Space Weather
194	Characterizing the Heliosphere; In Situ Plasma and Energetic Particle Environments; Responses to the Solar Cycle
195	Radial Evolution of the Solar Wind from the Sun to the Outer Boundaries of the Heliosphere
196	Solar flux and ionosphere-thermosphere system
197	Impact of Planetary Waves on Longitudinal Variations in the Ionosphere-Thermosphere
198	Solar eclipse and ionosphere-thermosphere coupling
199	Understand the underlying physical processes of solar energetic particles from their origins to the entire inner heliosphere
200	Ion-neutral coupling in heliophysics