Living with a Star Program Analysis Group (LPAG) Executive Committee (EC) 2023 Final Report

March 16, 2024

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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
Angelos Vourlidas, Johns Hopkins University Applied Physics Laboratory
Ian Cohen, Johns Hopkins University Applied Physics Laboratory
Olga Verkhoglyadova, NASA Jet Propulsion Laboratory
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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 2023 annual report to NASA Headquarters on the activities of the LPAG Executive Committee this year.

This year, the committee held two in-person meetings. The first was held May 25-26, 2023 in the Washington DC area, and the second was held December 5-6 2023 in College Park, Maryland. A brief virtual online meeting was also held Tuesday, October 10, 2023. The primary goal of the LPAG this year was to update the Focused Science Teams (FST) and that process has begun, with the first 13 of the remaining 2020 rollover FST's updated.

The May meeting included an overview of updates on the LWS website and discussion of the suggested reporting template for the FST (Section 3). Additional topics raised at this meeting concerned the overlap and differentiation between the LWS and Space Weather Program (Section 4), as well as discussions of the strategic role of Sun-climate science in the LWS program (section 5) and LWS support for ML/AI/ChatGPT initiatives (section 6). Further discussions involved current capabilities, gap analysis, and coordination with ground-based observatories (Section 7). The main focus of the May meeting, however, was the planning for the development of new Focused Science Topics (FSTs) (Sections 8, 9)

(NSF) Mangala Sharma (NOAA) Irfan Azeem (AFOSR) Julie Moses (ONR) Bruce Fritz/Dan Eleutario The report is organized as follows:

- (Section 3) FST management, reporting, and updates to the LWS Website;
- (Section 4) Overlap and Differentiation of the LWS and Space Weather Program;
- (Section 5) Strategic role of Sun-Climate science in the LWS program;
- (Section 6) LWS support of use of AI/ML in Heliophysics;
- (Section 7) Development of draft Roll-over Focused Science Topics (FSTs);
- (Section 8) Draft Roll-over Focused Science Topic Write-ups;

3 FST management, reporting, and updates to the LWS Website

The 2019 LPAG EC report contained findings on "Assessing Progress of Focused Science Topics (FSTs) in Addressing LWS Goals". The EC suggested that NASA Headquarters 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 this end, the LWS web development team has made progress in building a website that provides FST team reporting templates based on the reporting structure provided within the 2019 LPAG EC report. This site and reporting format were reviewed by the CE in May 2023 and found to be an excellent step forward.

One suggestion was to add the following link to the Heliophysics Web for "Science Highlights" in this reporting structure.

https://docs.google.com/forms/d/e/1FAIpQLSeI6f0mjUX-e19FD51GUdBf8rVLCvTTi4HBKzEjIN83V60kRQ/viewform?c=0&w=1

Another previous EC finding was the lack of connection with existing research community persistent identifiers (e.g., DOIs, ORCIDs, RORs). The EC found that significant work has been done to alleviate this in the new Team Reporting structure.

Finally, the EC notes that Team and Team Lead training for all FST teams and an annual'research showcase' (open to present and past teams) would be beneficial to the program.

4 Overlap and Differentiation of the LWS and Space Weather Program

The overlap and differentiation between the LWS and Space Weather program (SWP) was brought up for discussion at the LPAG meeting. Genene Fisher (NASA HQ) offered an explanation of the differences and synergies in the following url:

https://science.nasa.gov/heliophysics/space-weather-strategy

Genene Fisher also provided the following link to the 03-22-Space-Weather-R202R-Framework.

https://www.whitehouse.gov/wp-content/uploads/2022/03/03-2022-Space-Weather-R2O2R-Framework.pdf

The following "Space Weather Living History" interview with Madhulika Guhathakurta about a solar cycle ago was suggested to the committee as perhaps being useful.

https://solarsystem.nasa.gov/resources/2930/space-weather-living-history-podcast-featuring-heliophysicist-dr-madhulika-guhathakurta?category=heat

The general consensus of the LPAG EC was that the goals listed in the first link provided here are clear and application specific. However, the LPAG EC is concerned that the LWS/SWP potential divisions and boundaries remain confusing. The EC sees overlaps between the NASA and NOAA space weather research domains and between the NASA LWS and NASA Space Weather programs. The LPAG EC recognized that LWS science is system-wide and cross-disciplinary, leading from discovery to understanding, while the SWP leads from this understanding to operational prediction capability. The LPAG EC also recognized that LWS occupies a unique space in developing research topics that, in turn, generate new fields of research in Heliophysics. It was suggested that LPAG tried to articulate some of the ways the LWS and SWP programs overlap (thereby determining how they are distinct) and also reach out to the community to gather their perspectives.

5 Strategic role of Sun-Climate science in the LWS program

This year the important role of sun-climate science within the LWS was also discussed. As was pointed out, one of the 2019 FST's investigates new solar irradiance quantities (other than F10.7) for monitoring changes in the Earth's atmosphere and ionosphere. It was suggested that the committee could learn from the recent Jack Eddy Symposium (June 2022). At the symposium, there were three working groups (all with an underlying theme of open science methods): 1) The Interconnection of Sun, Climate, and Society; 2) Risk and Resiliency to Space Weather Disruption; and 3) (Exo)Planetary Atmosphere: the Impact of Stars and Solar Physics on Habitability and Life.

https://cpaess.ucar.edu/meetings/eddy-symposium-2022

Finally, a single white paper submitted to the Decadal Survey focused on the issue of Heliophysics Science Community Contributions to Addressing Climate Change.

http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads%2F623127%2F6920789%2F242-222e6ba6c96782eddeb27e7717cb2269_NossalSusanM.pdf

The CE recognized that sun-climate science is a central area of research within the LWS.

A possible topic to be considered in 2024 LPAG is to convene a SIG/SAG on Sun-climate connection to determine whether there are interest/compelling questions for future solicitation ideas.

6 LWS support of use of AI/ML in Heliophysics

In the two 2023 meetings, the EC discussed what LWS should provide for AI/ML initiatives. An outcome of these discussions was that the language should be broadened. ML is just a component of the overall data science discipline. Data science is vital to systems science and, hence, to LWS. The modified language suggested to convey the need for a broader view is 'data science comprises scalable architectural approaches, techniques, software, and algorithms that alter the paradigm by which data are collected, managed, analyzed, and communicated.' It was also pointed out that we are beyond the point of proof of concept for ML in Heliophysics. Many examples were presented to show that ML has already been useful across the Heliophysics area. A good summary of the current status is given in the following Decadal Survey white paper.

http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads%2F623127%2F6920789%2F107-1870187ec154eee48664bed68513f0cb_PoduvalBala.pdf

Currently, there is a ROSES23 program element on the topic of developing AI/ML ready data. "B16 Heliophysics Artificial Intelligence/Machine Learning-Ready Data." Whether this should be expanded in the future is still an area of discussion within the LPAG. It was recognized that there is a gap between these proof-of-concept studies and their impact (on science and predictive understanding). More emphasis on social infrastructure (e.g., helping individuals and groups connect via science, technique, skills.) is needed to overcome this gap.

One last finding of the LPAG was that ChatGPT, although interesting, is not something the LPAG needs to comment on.

7 Development of draft Roll-over Focused Science Topics (FSTs)

The committee released a Call for Community Input to LWS Focused Science Topics (FSTs) in mid-June 2023 soliciting topics and other feedback through the LWS website. Various committee members released this to the SPD, SHINE, GEM, CEDAR, AGU SPA communities. The FST process was described at the CEDAR meeting in June by Olga Verkhoglyadova and Bob McCoy, and also was discussed at the GEM meeting. A virtual Town Hall meeting was held on 13 July 2023 to further engage the community and clarify the feedback process. The deadline for entering new input and comments was July 21, 2023. When the site closed, in addition to the comments provided for the 13 roll-over FSTs, a set of 18 new FSTs were suggested.

The committee met online on October 10, 2023, and decided that for this year only the 13 remaining FSTs from the 2020 list (the rollover FSTs) would be revised and brought up to date for this year. These roll-over FSTs were finalized at the December 2023 meeting, and the remaining 18 new FSTs were handed over to the LPAG to be finalized in 2024.

At the December meeting, only 12 FSTs were finalized as two of the original 2020 roll-over FSTs were combined into one:

1. FST01 (formerly FST20-01, 212) Connecting Space Weather and Thermospheric Density and Composition
2. FST02 (formerly FST20-03, 213) Multi-scale High-Latitude Forcing of the Ionosphere-Thermosphere System
3. FST03 (formerly FST20-06, 214) Solar Eclipses as a Naturally Occurring Ionosphere-Thermosphere Laboratory
4. FST04 (formerlyFST20-07, 215) Ion-Neutral Coupling in the Ionosphere-Thermosphere System
5. FST05 (formerly FST20-09, 216) Connecting Auroral Phenomena with Magnetospheric Phenomena
6. FST06 (formerly FST20-14, 218) Physical Processes Responsible for the Generation and Evolution of the Solar Wind
7. FST07 (formerly FST20-16, 219) Solar Flare Energetic Particles and Their Effects in Large Solar Energetic Particle Events
8. FST08 (formerly FST20-17, 220) Understanding the Transport Processes of Solar Energetic Particles from Their Origins to the Entire Inner Heliosphere
9. FST09 (formerly FST20-18, 221) Extreme Solar Events — Probabilistic Forecasting and Physical Understanding
10. FST10 (formerly FST20-20, 222) Understanding Energy Partition and Energy Release Processes in Eruptive Events
11. FST11 (formerly FST20-21 & FST20-22, 223 and 224) Atmospheric Loss and Habitability in the Presence of a Star
12. FST12 (formerly FST20-12, 217) Understanding Space Weather Effects for Human Deep Space Flight

8 Draft Roll-over Focused Science Topic Write-ups

The draft FSTs presented here were generated from the unused FSTs from 2020, of which there were 13. Each of these FSTs were modified by the committee, brought up to date and with comments folded in. The thirteen unused 2020 FSTs are listed here, although it was decided to only put forward 11 FSTs as one was recommended for Space Weather funding (listed here as FST 12), anda two were combined. 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 Density and Composition
2. Multi-scale High-Latitude Forcing of the Ionosphere-Thermosphere System
3. Solar Eclipses as a Naturally Occurring Ionosphere-Thermosphere Laboratory
4. Ion-Neutral Coupling in the Ionosphere-Thermosphere System
5. Connecting Auroral Phenomena with Magnetospheric Phenomena
6. Physical Processes Responsible for the Generation and Evolution of the Solar Wind
7. Solar Flare Energetic Particles and Their Effects in Large Solar Energetic Particle Events
8. Understanding the Transport Processes of Solar Energetic Particles from Their Origins to the Entire Inner Heliosphere
9. Extreme Solar Events — Probabilistic Forecasting and Physical Understanding
10. Understanding Energy Partition and Energy Release Processes in Eruptive Events
11. Atmospheric Loss and Habitability in the Presence of a Star
12. Understanding Space Weather Effects for Human Deep Space Flight

FST.1 Connecting Space Weather and Thermospheric Density and Composition

Solar flares and geomagnetic storms impulsively introduce energy to the thermosphere, producing significant variations in atmospheric density and temperature, and modifications of the mesoscale dynamical structure of the upper atmosphere. The combined effect of these inputs also results in modification of upper atmospheric composition. With the gradual cooling and contraction of the thermosphere due to increasing abundance of carbon dioxide, orbiting debris accumulates faster than in the past, and the layers of the ionosphere are also descending. Understanding the variable modification of thermospheric state by external inputs is therefore of growing importance and motivates the development of improved atmospheric density and wind models, especially during geomagnetic storm periods. Related to drag, the chemistry and abundance of thermospheric odd nitrogen (NO, N) is extremely sensitive to temperature and will affect the NO/N ratio. 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 large uncertainty in density. A critical component of this variability are the highly variable inputs of geomagnetic storms and substorms; another comes from the transient effects of solar flares on the sunlit side of Earth. Geomagnetic storms have a more complex input with energy input to the atmosphere originating at high latitudes and potentially significant mesoscale structure and circulation. It can take several hours before the heating is globalized and this delay 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 thermo spheric density; to understand coupling between space weather (ionization, and heating and photo chemistry) and atmospheric composition (i.e., O/N2, and NO/N) 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: studying the 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 analysis techniques.

Notes to NASA 2020:

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

This FST is focused 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).

The 2020 FSTs 1, 5, and 7 all have applications to atmospheric drag.

Notes to NASA 2023:

This FST is a roll-over of 20-1.

A recent ROSES call investigated EUV, and there may be implications for this work.
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FST.2 Multi-scale High-Latitude Forcing of the Ionosphere-Thermosphere System

Coupling processes across a wide range of scales are important to understand energy redistribution in Earth's Magnetosphere-Ionosphere-Thermosphere system. In general, energy transfer from the magnetosphere into the ionosphere-thermosphere occurs in a variety of forms and scales. These processes at high latitudes include diffuse and discrete aurora and the associated particle precipitations and Poynting fluxes. Physical state variables 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 high latitudes, they are of global importance, as these drivers also generate meridional neutral wind and large scale traveling atmospheric and ionospheric disturbances (TADs and TIDs) that propagate toward the equator, transferring energy and composition perturbations to lower latitudes. Ultimately, 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. The dynamic results of these processes have important implications for ionospheric and thermospheric structure, including formation of localized ionospheric density structures that disturb GNSS signals and satellite operations. Multi-scale high-latitude forcing can also lead to significant changes in thermospheric composition and density at mid- and low-latitudes.

Bridging the gap from multi-scale electrodynamic forcing at high latitudes to global disturbances that impact lower latitudes in the ionosphere-thermosphere system remains an outstanding challenge. Additionally, new modeling and observational studies have indicated a significant connection between the polar vortex and traveling ionospheric disturbances, further establishing the importance of high-latitude vertical coupling processes. Dedicated community observational and theoretical efforts remain as an important study area for exploration of these connections and other related upper and lower atmospheric cooling processes at high latitudes, along with their impact on the global I-T system.

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. Whole atmosphere coupling, in particular lower - upper atmosphere feedback and interchange, is particularly rich field for model-data fusion applications.

Notes to NASA 2020:

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

Notes to NASA 2023:

This FST is a roll-over of 20-3.

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FST.3 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. IT science around eclipses remains open. For example, 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/and lower atmosphere, the sudden cooling in the atmosphere, coincidental convective and mountain waves from below and their amplification with altitude, or a combination of these and other processes.

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 the Arctic in June 2021, over Antarctica in December 2021 and two solar eclipses over North America in October 2023 and April 2024, an FST that develops models will have the opportunity to validate and test those predictions using recently acquired data. Models which utilize some new solar flux data or indices such as FISM2 can also be tested. The 2024 North American eclipse provides an opportunity for significant outreach on the importance of heliophysics science, in a way that can be directly experienced by the public. Several future eclipses are of great space-science interest as well, although not in the continental US: The August 2026 eclipse over Greenland and the August 2027 eclipse over Spain will allow us to study the polar and midlatitude ionospheric responses and their geospace impacts. Decent ground-based observations should be available to augment space-based observations.

Overview of Science Goals:

This topic is fundamental to understanding geospace responses to transient solar radiation changes that sweep through the entire solar-terrestrial system. Several new science questions have been raised regarding fundamental IT coupling processes. Investigations pursuing one or more of the following goals are invited: (1) traveling ionospheric and atmospheric waves (TIDs/TADs), excited by an eclipse, which may or may not form bow waves in the thermosphere and ionosphere; (2) the conjugacy or hemispheric coupling of the eclipse effects; (3) solar eclipse influences on the middle and upper thermospheric dynamics and electromagnetics, of particular significance for the ionosphere at low and equatorial latitudes; (4) solar-eclipse-induced neutral composition change; (5) residual solar flux variability and the ionization effect, and (6) high-latitude solar eclipse influences on the ionosphere-magnetosphere coupling. Investigations that seek to address outstanding IT questions arising from all available eclipse observations 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 so lar 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 magneto sphere, 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 phe nomena 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 analysis techniques.

Notes to NASA 2020:

This FST is recycled from the 2020 FST originally input 198

Notes to NASA 2023:

This FST is a roll-over of 20-6.

Comment: This is an important and timely topic of research, given the two solar eclipses in the US (recent and upcoming). The NASA IES program has funded some recent eclipse studies. Unfortunately, the 2024 eclipse study seems not well funded. The community needs dedicated team efforts to study the eclipse effect. The eclipse study would be a great focus topic for a team effort. The team can focus on a specific eclipse with diversified members to address difference aspects (EUV effects, waves, local, regional, and geospace effect). The team could also conduct comparative eclipse studies addressing different effects in different geographic locations.

Comment: Several future eclipses are of great space science interest as well, although not in the continental US: The August 2026 Greenland and August 2027 Spain eclipses will allow to study the polar and midlatitude ionospheric responses and their geospace impact. Decent ground-based observations should be available.

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FST.4 Ion-Neutral Coupling at Multi-scales in the Ionosphere-Thermosphere System

The dynamic interaction between plasma and neutrals in the upper atmosphere impacts how the ionosphere responds to energy and momentum inputs from the solar wind/magnetosphere and the lower atmosphere. A critical component of these ionosphere-thermosphere (IT) interactions is the variety of ion-neutral coupling processes under diverse forcing conditions. Addressing specific unresolved issues involving ion-neutral coupling within the IT system is the focus of this FST.

This topic involves dynamic processes across latitudinal regimes. In the high latitudes, in regions such as the polar cap and auroral zone where direct coupling occurs across geospace boundaries, mass, momentum, and energy transfer between the IT system and the magnetosphere are highly efficient. It is in these interface regions, where ions respond rapidly to external solar wind/magnetosphere driving forces, that the ion-neutral collisions (ion drag) play an essential role in converting convection flows into heat. This is likely a major source of heating for the ionosphere and thermosphere, especially under strong solar wind and geomagnetic driving conditions, and one of the major sources for thermospheric wind circulation changes.

In the equatorial and low latitude regions, significant gaps exist in our understanding of how ion-neutral coupling forms prominent ionosphere and thermosphere features, such as the equatorial anomalies in the plasma and neutral densities, temperature, and wind. Additional gaps in our knowledge include the ionospheric seasonal variations known as the winter anomaly, the Weddell Sea Anomaly (WSA) and the midlatitude summer night anomaly (MSNA). There are also knowledge gaps on how the ion-neutral coupling regulates thermospheric circulation and temperature distribution, including day-night differences. 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 the above examples, much progress is needed to deepen understanding of how the exchanges of momentum, energy, and mass occur and their impact. 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 these fundamental phenomena and the physics of ion-neutral coupling is understood better in the near-term.

Overview of Science Goals:

The specific science goals of this FST can be divided into different latitudinal regions, and studies of cross-latitudinal coupling should be encouraged as well. Each goal would include significant model development.

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 ionospheric dynamics, and the role of ion-neutral coupling in the dynamic changes of the ionosphere equatorial ionization anomaly (EIA), including its diurnal, seasonal (semiannual and annual) variations and hemispheric asymmetry, and how these neutral and plasma anomalies respond to geomagnetic disturbances.

For ion-neutral coupling in the middle latitudes, the science goals are to understand ionospheric climatological phenomena, such as ionospheric winter anomaly, midlatitude summer night anomaly and WSA, and to elucidate the roles of the neutral winds and composition, electric fields, and the topside plasma influx on the formation of these anomalies.

At both low and middle latitudes, the science goals also include understanding how the ion-neutral coupling, especially the changes of the ionosphere with season and solar cycle, impacts thermospheric circulation and temperature structures, such as the summer-winter meridional circulation and the equinox transition of both the ionosphere and thermosphere.

For ion-neutral coupling in the sub-auroral and high-latitude regions, the science goals are to characterize the neutral wind and temperature changes, and potentially composition changes, associated with sub-auroral high speed polarization streams (SAPS); to study the high latitude winds driven by plasma convection and temperature changes due to Joule heating; ion/neutral upwelling associated with global circulation changes that impacts the storm-time composition and ionospheric density. Additional science goals are also to understand how the winds, composition and temperature perturbations propagate to middle and low latitudes, and the effects of disturbance neutral wind dynamo and penetration electric fields on global ionospheric distribution, 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 LWS Strategic Science Areas (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 spacecraft traffic management and provide information of ionospheric environment for navigation and communication.

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. New observational capabilities will be able to feed into modeling efforts. For example, the upcoming EZIE mission is expected to provide information on mesoscale structures in the electrojet. On the thermosphere side, horizontally-resolved mesoscale wind observations are becoming available from networks of meteor radars. High resolution winds combined with ionospheric parameters are key for interpreting mesoscale structures. Additionally, ion-neutral coupling at mesoscales are particularly relevant to studying the effects of solar eclipses and extreme events in the troposphere (e.g. volcanic eruptions, cyclones).

Specific investigations could include but are not limited to: thermospheric and ionospheric responses to geomagnetic storms; drivers and responses of thermospheric and ionospheric variability using coupled models and observations. TADs/TIDs generated in the polar region and their global propagation; global and regional SAPS effects, mechanisms of ionospheric and thermospheric anomalies, IT seasonal and hemispheric variations.

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

Notes to NASA 2020:

Notes to NASA 2023:

This FST is a roll-over of 20-7.

Comment: We strongly support this topic and would additionally like to highlight the importance of mesoscale coupling processes. New observational capabilities will be able to feed into modeling efforts. For example, the upcoming EZIE mission is expected to provide information on mesoscale structures in the electrojet. On the thermosphere side, horizontally-resolved mesoscale wind observations are becoming available from networks of meteor radars. High resolution winds combined with ionospheric parameters are key for interpreting mesoscale structures. Additionally, ion-neutral coupling at mesoscales are particularly relevant to studying the effects of solar eclipses and extreme events in the troposphere (e.g. volcanic eruptions, cyclones).

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FST.5 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 aurorae.

Aurorae are ultimately powered by the solar wind driving magnetospheric-ionospheric convection. The optical aurora phenomena represent a critical path for transfer and conversion of energy stored in the magnetosphere to the ionosphere-thermosphere system, which also energizes particles, drives high-latitude ionospheric currents, ionizes the upper atmosphere, heats the ionosphere and upper atmosphere, and powers ionospheric upflows/outflows. In addition, the aurora associated energy extraction and ionospheric upflow/outflow 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 can occur during quiet times and 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: cusp aurora, polar cap arcs, poleward boundary intensifications, streamers, quiet and growth-phase arcs, omega bands, westward traveling surge, giant undulations, pulsating patches. The recently discovered STEVE emission is another aurora-like phenomenon.

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 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. This FST is relevant to several LWS Strategic Science Areas in relation to ionospheric connectivity (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:

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 connectivity 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 2020:

This 2020 FST is a merger of roll-over 169 with three community comments.

Notes to NASA 2023:

This FST is a roll-over of FST 20-9.

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FST.6 Physical Processes Responsible for the Generation 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-coordinated 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 are the relative importance of plasma waves and interchange reconnection 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 Alfvénic 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, and upcoming observations from e.g., 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.

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. 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 align and compare PSP observations with observations at SolO and at 1 AU.
- Studies in which two or more competing theories could be judged with simulations and data.
- Re-analysis of historic data sets, e.g Helios, and comparison against PSP and SolO measurements
- 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 analysis techniques.

Notes to NASA 2020:

None.

Notes to NASA 2023:

This FST is a roll-over of 20-14.

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FST.7 Solar Flare Energetic Particles and Their Effects in Large Solar Energetic Particle Events

A critical component of the LWS program is to understand energetic particles accelerated during solar eruptive events. These particles, known as solar energetic particles (SEPs), are accelerated by solar flares or at shocks driven by coronal mass ejections (CMEs). As they can produce various space weather effects, their study is integral to space weather research. Notably, particles accelerated by flares generate high-energy emissions, such as X-rays and gamma-rays, which can ionize the thermosphere and ionosphere. Some of these particles transport through the solar eruption regions, escape the solar corona, and enter interplanetary (IP) space, contributing to impulsive SEP events.

The escaped flare energetic particles include electrons, protons, and minor components such as 3He, heavy, and ultra-heavy ions, with compositions that are often anomalously different from those in the solar corona and solar wind. This indicates that the acceleration processes are different from the traditional shock acceleration. These particles are thought to contribute to large SEP events primarily produced by CME-driven shocks, by providing pre-accelerated suprathermal 'seed' particles. However, the mechanisms underlying their acceleration by solar flares and their specific roles in contributing to large SEP events are not well understood, posing a significant challenge with numerous scientific objectives to be pursued in order to advance our understanding of the associated space weather effects further.

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 contributions to large SEP events. 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 differ- ent 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 welcome (but not required) in this FST, including explainable, interpretable, and traceable methods. .

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 at the source region and their relation.

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

Notes to NASA 2020:

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

Notes to NASA 2023:

This FST is a roll-over of 20-16.
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FST.8 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 reflect a mixture of different physical processes occurring during the particle acceleration and their transport to Earth. Because of this ambiguity, a comprehensive understanding of the physical mechanisms and the relative importance of origin vs transport processes in SEP events is still lacking. With the advent of distributed 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) and associated shock waves, 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, shock waves and coronal or 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:

- What factors control the observed SEP properties, such as intensity, energy spectra, composition, and temporal evolution?
- How is the SEP evolution influenced by interplanetary transport, magnetic connectivity, and heliospheric structures?
- 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, and the expanding ground-based radio interferometric capabilities, which will offer new insight on the generation and transport of SEPs. Such insights are keenly needed to support the upcoming human exploration of the moon under the Artemis program and the future Mars exploration plans. 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:

1. Demonstration of a capability to quantitatively describe individual SEP events using multiple spacecraft observations and to derive and distinguish different transport effects.

2. Addition of numerical modeling and theoretical studies for studying and distinguishing different particle transport processes and evaluation of their relative importance.
3. Inform mitigation strategies for human deep space flight by quantifying the radiation environment in different areas of the solar system.
4. Demonstration of agreements between model predictions and observations for SEP events

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 energetic particle transport.

This topic also addresses two Key Science Goals (KSG) of the 2013 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:

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 both beyond and closer to the Sun (e.g., PSP, SolO, ACE, GOES, Wind, MAVEN, etc) and ground-based assets, such as radio arrays. 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, including explainable, interpretable, and traceable methods.

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, shocks, 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 analysis techniques.

Notes to NASA 2020:

None

Notes to NASA 2023:

This FST is a roll-over of 20-17.

This FST (8) is focused on transport processed whereas FST 7 is focused on particles originating in solar flares.

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FST.9 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. 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. The latter is of critical timeliness as the NASA Artemis program is underway to establish a long-term human presence on the moon and beyond within the next decade. 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 is relevant to several 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. There is a potential benefit of utilizing ML/AI in the analysis of this topic are welcome (but not required) in this FST, including explainable, interpretable, and traceable methods. .

This FST would benefit from the following:

- Data Analysis
- Data Model Comparison
- Database Development
- Simulations
- Theory and Model Development

- Tools and Analysis Techniques

Notes to NASA 2020:

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 was an 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.

Notes to NASA 2023:

This FST is a roll-over of 20-18.

There is a decadal survey paper on (469) Extreme Solar Radio Bursts.

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FST.10 Understanding Energy Partition and Energy Release Processes in Eruptive Events

Coronal mass ejections (CMEs) are one of the major drivers of space weather and constitute one of the major hazards posed by solar activity. An overarching goal 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 starts, the partition of the released energy among heating, acceleration, and the other terms, and distribution among 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.n

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 2013 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. Available data sources include PSP, SO, STEREO, ACE, Wind, Hinode and IRIS, as well as ground-based assets such as EOVSA, DKIST and BBSO, among others. New data sources will be available in the near future such as PUNCH, MUSE and EUVST. 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 analysis techniques.

Notes to NASA 2023:

This FST is a roll-over of 20-20 from 2020

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FST.11 Atmospheric Loss and Habitability in the Presence of a Star

The overarching goal of this FST is to explore the atmospheric loss and habitability of a planet (including Earth) through its interaction with the host star. To achieve this goal, investigating various escape mechanisms that lead to the loss of atmosphere to space from both unmagnetized and magnetized planets is necessary. Meanwhile, understanding the impact of stellar XUV radiation, stellar winds, stellar activity, and associated SEPs (of the Sun and young Sun-like stars as well as G, K, and M-dwarfs) on planetary atmospheres is necessary to understand the habitability of early Earth and other terrestrial planets in the solar system and beyond. Comparing the processes that lead to atmospheric loss to space 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. Atmospheric escape, however, remains a highly complex problem. 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 well understood. While estimates of the total escape rates for Mars and Venus (without an intrinsic dipole magnetic field) are on the order of 1025 particles per second, estimates for magnetized Earth are spread over a broader range of 1024 to 1026 particles per second, primarily due to the intricate ionospheric and magnetospheric processes and pathways for ultimate escape that arise from the funneling of solar wind energy to the magnetic poles. Another critical aspect is the level of ionizing radiation and particle fluxes in the planetary space environment. The origin of stellar eruptions from different types of stars is not well understood given that observations targeting a sample of flaring stars seemed to suggest a lack of CMEs, which have profound implications on the exoplanet habitability.

Given the wealth of data from Earth (Cluster, MMS, and many more), Mars (Mars Express, Mars Global Surveyor, and MAVEN), Venus (Pioneer Venus Orbiter, Venus Express, and Akatsuki), Titan (Cassini), Pluto (New Horizons), terrestrial exoplanets (JWST), and the upcoming missions of EscaPADE, Mars 2020, VERITAS and DAVINCI as well as the stellar flare observations from Kepler and TESS, it is timely to seek a quantitative assessment of our current understanding of atmospheric loss and the factors that control it, both from the observational viewpoint and theoretical modeling approaches.

Overview of Science Goals:

Key science goals of this FST include: 1) Determining how planetary atmospheres lose to space as well as the channels through which the depletions occur, 2) Understanding the origin of stellar eruptions and the effects of stellar radiation, winds, magnetic activity, and stellar evolution on the planetary atmospheric escape and habitability, and 3) Investigating the impact of planetary atmospheric composition, size, obliquity, orbital eccentricity, and the presence of magnetic fields on the planetary atmospheric escape and habitability.

Measures of success could include:

- Capability to assess the origin of stellar activity (e.g., flare-CMEs and flares without CMEs) on the Sun and more active, young Sun-like stars as well as G, K, and M-dwarfs.

- Capability to assess the impact of stellar radiation and winds, magnetic activity (e.g., flares and CMEs), and the associated energetic particles on planetary atmospheric loss to space.

- Capability to assess the significance of planetary atmospheric composition, size, obliquity, orbital eccentricity, and magnetic fields for planetary atmospheric loss to space.

- Capability to assess the roles of stellar impact and its evolution on integrated atmospheric loss, atmospheric evolution through time, 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 and planetary magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

This FST is relevant to the 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. The FTS will also promote developing a broader understanding of solar extreme activity with respect to solar evolutionary changes. 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 can leverage the current solar model and magnetospheric, ionospheric, and thermospheric models of the Earth, Mars, Venus, and other planets within our solar system to aid in developing sophisticated multi-dimensional multi-fluid models that can be applied to study atmospheric loss to space from terrestrial planets around the Sun and stars of different ages and/or types.

Types of investigations could include:

- Utilization of the existing heliophysics models (i.e., solar models and coupled planetary magnetosphere-ionosphere-atmosphere models) and observational datasets from multiple spacecraft to investigate atmospheric loss to space from planets of different atmospheric composition, size, obliquity, orbital eccentricity, and magnetic fields through their interactions with the host stars.

- Investigations of solar/stellar impacts (including XUV radiation, winds, and eruptions) on planetary atmospheric loss to space based on analyses of observational datasets from multiple spacecraft and theory/modeling approaches.
- Development of modeling approaches to extend solar corona, wind, and eruption models to young Sun-like stars and other types of active stars based on inputs from solar and stellar observations (e.g., XUV radiation, magnetic fields, and flare-CMEs).
- Development of modeling approaches to extend the planetary ionosphere/thermosphere and magnetosphere models to early Earth, Mars, Venus, and exoplanets (with broad parameter space) that may experience much severer stellar environments.
- Development of modeling approaches and observational strategies (such as data extrapolation techniques) to investigate the stellar impact and its evolution on integrated atmospheric loss, atmospheric evolution through time, and planetary habitability.

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

Notes to NASA 2023:

Notes to NASA 2023: This FST is a merger of 20-21 20-22 with community input ID 235.

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FST.12 Understanding Space Weather Effects 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 important that we understand the solar impacts within and around the lunar environment, which has significant 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 critically analyze relevant information and science results from relevant research groups to develop a physics-based approach for radiative protection of astronauts and space assets on cislunar orbits. 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 recommendations for 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 individ ual 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 hu man space travel and 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 2020:

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 towards understanding space weather hazards encountered during 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.

Notes to NASA 2023:

This FST is a roll-over of 20-12.

Can be discussed in coordination with and in relevance to priorities of the R2O program.

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9 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