COLLEGE OF ENGINEERING
CLIMATE AND SPACE SCIENCES AND ENGINEERING
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Dr. Nicola Fox, Heliophysics Division Director
National Aeronautics and Space Administration
Heliophysics Division
300 E Street, SW
Washington, DC 20546-0001

Dear Dr. Fox:

The Heliophysics Advisory Committee (HPAC), an advisory committee to the Heliophysics Division (HPD) of the Science Mission Directorate (SMD) of the National Aeronautics and Space Administration (NASA), convened on 27 October 2021 via Webex virtual connection. The undersigned served as Chair for the meeting with the support of Drs. Kelly Korreck and Janet Kozyra, HPAC Designated Federal Officers (DFO), of NASA-HPD (incoming and outgoing, respectively).

All of the members of HPAC participated. Specifically, those present were as follows:

- Aroh Barjatya (Embry-Riddle Aeronautical University)
- Rebecca Bishop (The Aerospace Corporation)
- Paul Cassak (West Virginia University)
- Patricia Doherty (Boston College, Space Weather Council chair)
- Matina Gkioulidou (Johns Hopkins University Applied Physics Laboratory)
- Larisa Goncharenko (Massachusetts Institute of Technology Haystack Observatory)
- Allison Jaynes (University of Iowa)
- James Klimchuk (NASA Goddard Space Flight Center)
- Therese Moretto Jorgensen (NASA Ames Research Center, vice chair)
- Michael Liemohn (University of Michigan, chair)
- Tomoko Matsuo (University of Colorado)
- Mari Paz Miralles (Smithsonian Astrophysical Observatory)
- Cora Randall (University of Colorado, Boulder)
- Kristin Simunac (St. Petersburg College)

Also in attendance for the first half of the meeting were representatives from the Earth Science Advisory Committee and the Planetary Science Advisory Committee, Drs. Sara Tucker and Conor Nixon, respectively.

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Jennifer Kearns briefed the HPAC about the Government Performance and Results Act - Modernization Act (GPRAMA) process for 2021. The HPAC was tasked to lead the review of two of the SMD performance goals:

PG 1.1.1. NASA shall demonstrate progress in exploring and advancing understanding of the physical processes and connections of the Sun, space, and planetary environments throughout the Solar System.
PG 1.1.6. NASA shall demonstrate progress in developing the capability to detect and knowledge to predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.

Also, specifically within PG 1.1.6, we were requested to assess NASA's performance on this subgoal:

*To include specific consideration/rating for progress in advancing scientific understanding of background solar wind, solar wind structures, and coronal mass ejections, which can be integrated into key models used to predict the arrival time and impact of space storms at Earth.*

Resulting from substantial deliberation, **all present voted unanimously for a "green" rating for both of these performance goals**, finding "expectations for the research program fully met in context of resources invested." The specific summary text generated by HPAC for each of the performance goals can be found below.

HPAC has a recommendation for NASA regarding the SMD GPRAMA process. We recommend that the evaluation of PG1.1.8, about characterizing the behavior of the Earth system, include a representative from HPAC for the discussion and vote. **Our full recommendation is as follows:**

> The connection between Heliophysics science and Earth sciences brought up by the ESAC representative during the HPAC meeting (https://aura.gsfc.nasa.gov/science/feature-20210405.html) and demonstrated by the TIMED-SABER study highlighted in the GPRAMA PG 1.1.6 report, underscores the benefits of coordination between the Heliophysics Directorate and Earth Science Directorate to create interdisciplinary research opportunities, and to collaborate on strategic programs to tackle pressing issues like climate variability and its impact on space systems and environment (e.g. space traffic management). Specifically, we recommend that HPAC, as a supporting discipline, formally contributes to the future annual GPRAMA science evaluation of PG 1.1.8: "*NASA shall demonstrate progress in characterizing the behavior of the Earth system, including its various components and the naturally occurring and human-induced forcings that act upon it*". This recommendation is aligned with the HPD's vision for expanding Heliophysics' reach into other disciplines, and helps enhance the visibility and appeal of the Heliophysics discipline to the next generation of students who grew up witnessing the impact of extreme weather events and climate variability on our environment and societies.

HPAC then heard an update from Dr. Fox about the state of the Heliophysics Division. This was followed by an extensive questions and answer time with her, which was greatly appreciated by the committee. HPAC is excited about the upcoming mission opportunities within HPD, the missions in selection and development like HERMES and GDC, the ongoing planning for the next Solar and Space Physics Decadal Survey, and the planning for the Heliophysics Big Year with solar eclipses in both 2023 and 2024 and the expected solar maximum.

A couple of suggestions arose during the Q&A. The first was a more consistent budget and selection reporting pattern for the Research and Analysis (R&A) programs. This year, the President's budget request to Congress appeared to have a substantial cut in HPD R&A funding, but we were reassured by HPD staff that this is not the case but rather a consequence of one-time expenses or shifts in programmatic accounting. It would be useful to release a separate supplemental document that tracks R&A program funding across several years; this will greatly help the research community understand the annual variations. The second comment is that HPAC would like to hear more about the inclusivity, diversity, equity, and accessibility (IDEA) efforts with HPD. This could be a topic of presentation and discussion at the next HPAC meeting.

We thank the HPD staff for providing source material with highlights from the NASA-supported missions and research projects. This was most helpful in our assessment of the performance goals for the GPRAMA review. We welcome any requests from NASA Heliophysics Division for clarification or elaboration on our findings.

Sincerely yours,

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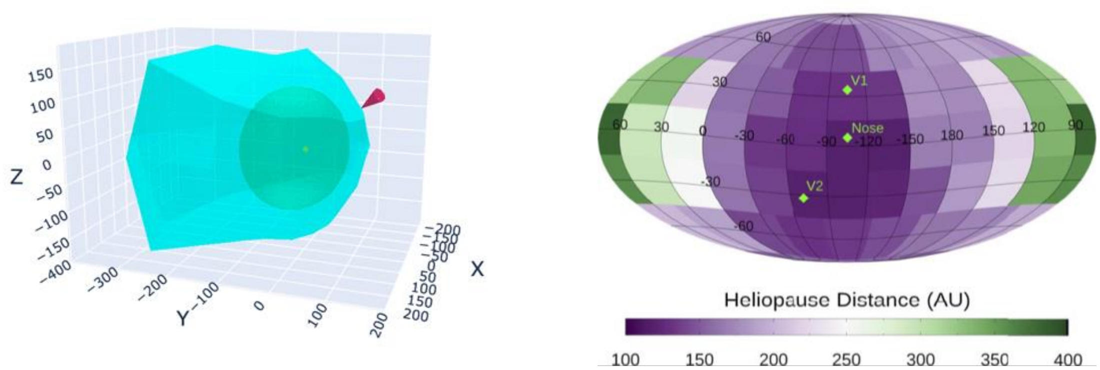
**1.1.1: NASA shall demonstrate progress in exploring and advancing understanding of the physical processes and connections of the Sun, space, and planetary environments throughout the Solar System.**

The Heliophysics Advisory Committee (lead), Planetary Advisory Committee, and Earth Science Advisory Committee determined in October 2021 that NASA has demonstrated progress in its annual performance towards exploring and advancing understanding of the physical processes and connections of the Sun, space, and planetary environments throughout the Solar System.

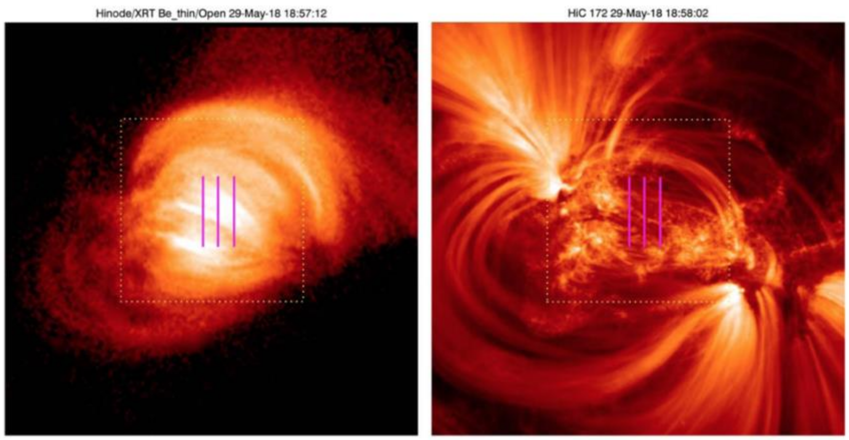
Below are examples of scientific progress reported in FY 2021.

Observations from the Interstellar Boundary Explorer (IBEX) launched in 2009 now cover more than a full solar cycle. This extended dataset of energetic neutral atom (ENA) flux from the outer heliosphere continues to improve our understanding of the shape and nature of the outer reaches of the solar system. Long term variations in the solar wind have been tracked in the observations and from the measured time differences of 2 to 6 years, or more, depending on ENA energy and look direction, the distances to the ENA source region in all directions have been derived. The resulting 3D map of the heliosphere covering the entire sky showed that the minimum distance from the Sun to the heliopause is about 120 AU (astronomical units) in the direction facing the interstellar wind, and in the opposite direction, it extends at least 350 AU, which is the distance limit of the sounding technique. The map represents the first actual measurements of this illusive outer heliosphere boundary that physics models have theorized about for a long time.




*Daniel B. Reisenfeld et al. (2021), A Full Solar Cycle of Interstellar Boundary Explorer (IBEX) Observations, ApJS 254, 40; doi: 10.3847/1538-4365/abf658*

The Sun exhibits a wide variety of explosive phenomena, ranging from tiny nanoflares that heat the corona, to microflares, to giant eruptive flares. Understanding the physical mechanisms that produce these explosions requires information on the distribution of event sizes and occurrence frequencies, as well as the resulting temperature distributions. Recent results have provided valuable new information on all three fronts. Coordinated observations from the Hi-C sounding rocket and the Hinode, IRIS, SDO, and RHESSI missions have revealed that nanoflares occur at a high frequency in the cores of active regions. Observations from Solar Orbiter have revealed that intermediate-size events called “campfires” are far more numerous than previously known. Coordinated observations from the FOXSI sounding rocket, Hinode, and SDO have revealed that microflares are multi-thermal, each characterized by a range of temperatures. These results, when combined with sophisticated numerical simulations, are helping us better understand the physical origins of explosive energy release on the Sun and throughout the universe.




Near-Sun observations from Parker Solar Probe (PSP) and Solar Orbiter have been combined with data from multiple vantage points in heliolongitude near 1 AU to provide new insights into solar processes and how they are coupled with conditions in the inner heliosphere for transient events and quiescent times. PSP, Solar Orbiter, STEREO-A, and ACE observed a Solar Energetic Particle event in late 2020 associated with an M-class flare and accompanying CME. Differences in the timing and intensity of arriving energetic ions can be used to test and constrain models of the shock acceleration mechanism and transport of radiation through the heliosphere. *In situ* magnetic field measurements from PSP, STEREO-A and Wind collected from August 2018 to July 2020 indicate similar magnetic flux over heliocentric distances from 0.2 to 1 AU. This does <u>not</u> support magnetic field evolution with radial propagation of the solar wind as an explanation for the differences between measured flux near 1 AU and the predicted values from existing models based on coronal fields and outflow with the solar wind from coronal holes.

The Magnetospheric Multiscale (MMS) mission was used to study how charged particles in the plasma in Earth’s magnetotail are accelerated to very high energies via the process of magnetic reconnection, where a change in the connectivity of magnetic field lines allows for the explosive release of magnetic energy. In one study, the three-dimensional magnetic structure and electron flow velocities in and around magnetic reconnection events was reconstructed. In another study, it was found that electrons are accelerated near the location where the magnetic connectivity changes. In a third study, it was found that features of low energy electrons near the reconnection site retain their structure as they accelerate and travel thousands of kilometers away. This suggests the mechanism accelerating the particles acts on all particles coherently. These results provide a new understanding of how charged particles are accelerated during magnetic reconnection in Earth’s magnetotail, which is important for understanding the plasma that is

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injected to the inner magnetosphere during geomagnetically active times. It is also important for understanding charged particle acceleration in solar flares and planetary magnetospheres throughout the solar system and the universe.

As NASA's Ionospheric Connection Explorer (ICON) mission moves past its two-year launch anniversary, it continues to provide new insights in lower atmosphere and ionosphere coupling, especially during the last deep solar minimum. For example, ICON's in situ observations have recently shown large O+ depletions that start in the post-midnight sector and persist until dawn. Similarly, ICON's simultaneous observations of equatorial neutral winds along with equatorial ionospheric currents from the European Space Agency's Swarm satellite mission have provided additional detailed insight into how neutral winds drive the currents that form the equatorial electrojet. These observations are playing a crucial role in improving our understanding of thermosphere-ionosphere coupling, and consequently our modeling capabilities as well. This is a clear demonstration that the ICON mission is living up to its name.

Relying on measurements from the Mars Climate Sounder (MCS) onboard the Mars Reconnaissance Orbiter, it was found that solar tides are responsible for much of the spatial-temporal variability in the Martian upper atmosphere. The tidal spectrum at 76 km above the Martian surface for a full Mars year was derived from MCS observations and found to agree well with the Mars Climate Database (MCD), which provides predictions from the Laboratoire de Meteorologie Dynamique Mars Global Climate Model. The MCD was used to predict density variability at altitudes up to 170 km in the Martian atmosphere, and to understand the physical processes that affect the vertical propagation of tides from lower heights. The MCD-MCS agreement demonstrates the potential of an MCS-validated MCD to provide new insights into thermosphere density variability at Mars due to vertical coupling by solar tides.

Daily solar irradiance measurements from the NASA Aura Ozone Monitoring Instrument (OMI) and the Dutch Tropospheric monitoring instrument (TROPOMI) were used to show that solar line activity indices in three upper Balmer lines (H$\beta$, H$\gamma$ and H$\delta$) closely track Total Solar Irradiance (TSI) on solar rotation timescales. These line activity indices deviate from the behavior of line activity indices that track chromospheric activity, particularly during passage of big sunspot groups. The results from the study rely upon the low noise levels in solar activity indices afforded by the excellent instrument stability of the OMI and TROPOMI instruments. The study concludes that solar activity patterns may be driven by different sources, with implications for the interpretation of measurements conducted in the search for extrasolar planets. This is a superb example of synergies between Earth Science and Heliophysics missions.

Citizen science recently led to the discovery of a new form of aurora called “dunes,” which consists of a modulation of the brightness in the green diffuse aurora, forming regularly spaced, parallel stripes of brighter emission. Observations from NASA’s Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission were critical to revealing the physical process responsible for this auroral feature. Working together, professional scientists in Europe, citizen scientists, and TIMED team members developed a plausible theory to explain the origin of the “dunes.” Specifically, analysis of the TIMED observations showed that the atmospheric temperature profile within the 60–110 km altitude range exhibits features of an atmospheric

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wave type known as a mesospheric bore, which is hypothesized to cause the dune-like auroral structure. The effort showed the viability of citizen science in contributing to leading-edge discoveries in solar-terrestrial physics.

The committee plus the ESAC and PSC (16 people) voted ***unanimously** for a GREEN* rating.

**PG. 1.1.6. NASA shall demonstrate progress in developing the capability to detect and knowledge to predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.**

The Heliophysics Advisory Committee determined in October 2021 that NASA remained on track in its annual performance towards achieving this performance goal. Below are examples of the scientific progress reported in FY 2021. The studies highlighted in the GPRAMA PG 1.1.6 report directly address the extreme space weather events (e.g., coronal mass ejections, solar energetic particles, and geomagnetically induced-currents) that are known to compromise and/or cause substantial harm to the national security, economy, and crewed and unmanned space activities as documented in the National Space Weather Strategy and Action Plan released in 2019. We would like to commend the HPD's strategic efforts to support targeted research and analysis activities that directly align with the National Strategy and Action Plan priorities.

Below are examples of the scientific progress reported in FY 2021.

Geoelectric fields produced during space weather events can result in geomagnetically induced currents (GIC) that are a considerable risk to technological systems. A recent study using coordinated observations from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission, ground-based magnetometers and radars, and the ground-based Earthscope facility has revealed the direct coupling of near-Earth space environmental conditions in the magnetotail to ground-level electromagnetic conditions. Findings from the study are expected to lead to better characterization and prediction of geoelectric signals from ultra-low-frequency waves that can reach amplitudes critical for causing intense geoelectric fields and GIC. This work advances the effort to predict space weather impacts at the surface.

Solar energetic particles (SEP) are the most hazardous outputs from solar activity and present a major danger to life in the deep space environment. The sources of highly energized particles ejected from the Sun are highly variable and challenging to trace through interplanetary space. A recent discovery derived from complementary observations made by the Hinode, Solar Dynamics Observatory (SDO), and Wind missions, has shown that the plasma composition of the most damaging SEP detected in the near-Earth space can be traced back to the confined magnetic field environment in the Sun's lower atmosphere. The mechanisms by which SEPs are accelerated to high energies and escape the Sun into interplanetary space are not well understood. However, a recent study that utilizes observations from the Parker Solar Probe, the Solar and Heliospheric Observatory (SOHO), the Solar TERrestrial Relations Observatory (STEREO), and the SDO

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missions confirms previous hypotheses of particle acceleration mechanisms. These works utilize the Heliophysics System Observatory in a resourceful way to discover the source of the most damaging class of SEP and to validate particle acceleration mechanisms, i.e. shock acceleration, helping to further our understanding of geoeffective space weather.

Thermospheric mass density changes have a considerable impact on the aerodynamic drag on space vehicles and space debris in the near-Earth space environments. 95% of all objects that are currently tracked are in fact debris. Cooling of the mesosphere and lower thermosphere (MLT) is known to result in a decrease in the temperature and density of the upper atmosphere up to at least 1000 km in altitude, which in turn leads to longer lifetimes for debris, increasing the chance of catastrophic collisions with valuable space assets. A recent study with long-term observations from the Thermosphere Ionosphere Mesosphere Energetics Dynamics (**TIMED**)-Sounding of the Atmosphere using Broadband Emission Radiometry (**SABER**) has revealed that the MLT has cooled dramatically since 2002, by as much as 2 to 22 Kelvin and also strongly suggests that the MLT in 2020 was colder than at any other time since the late 1700's. The study attributes the long-term cooling effects of the MLT to increasing carbon dioxide due to climate changes and weakening solar cycles. This finding will have a profound implication on the burgeoning space economy. The study also represents a significant achievement of theTIMED mission over the last 20 years.

In addition to the above examples, the committee was charged with providing a focused examination of the progress related to *understanding of background solar wind, solar wind structures, and coronal mass ejections, which can be integrated into key models used to predict the arrival time and impact of space storms at Earth.* This was accomplished by developing new methodologies to understand coronal mass ejection propagation using heliospheric images from the STEREO mission, which significantly lowered uncertainties on the time-of-arrival prediction at Earth. Furthermore, there has been significant progress made in global integrated models of the solar corona and heliosphere, in particular to understand the build-up of magnetic energy that leads to solar eruptive events that can generate space storms at Earth.

The committee of 14 people voted ***unanimously*** *for a GREEN* rating.

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