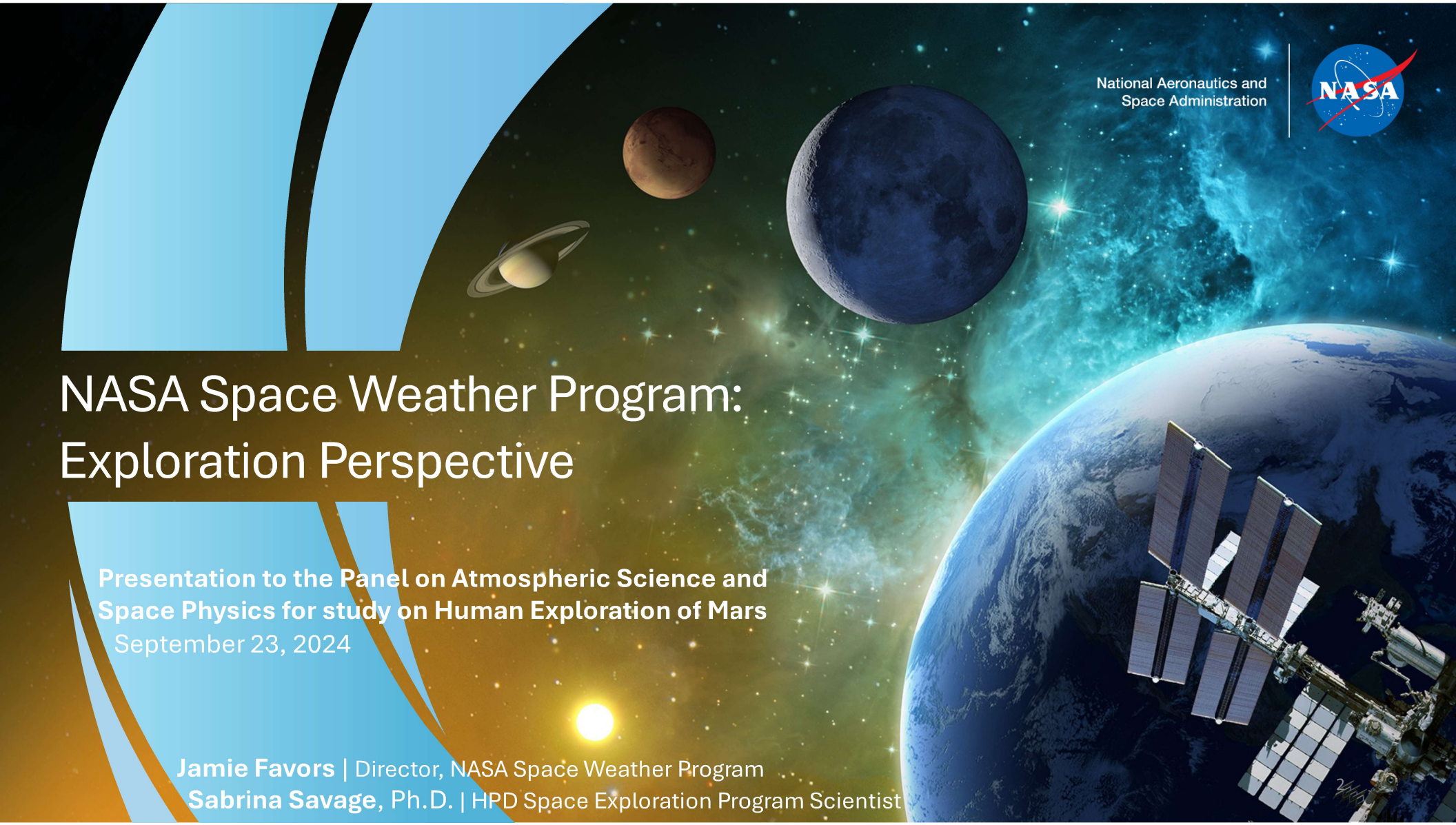


NASA Space Weather Program: Exploration Perspective

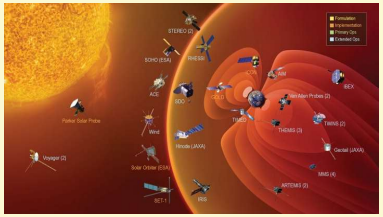
Presentation to the Panel on Atmospheric Science and Space Physics for study on Human Exploration of Mars
September 23, 2024

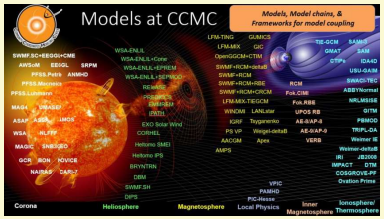
Jamie Favors | Director, NASA Space Weather Program
Sabrina Savage, Ph.D. | HPD Space Exploration Program Scientist

NASA Space Weather Program

[Current*] Vision, Mission, and Strategy

1. **Observe**
   - Advance observation techniques, technology, and capability
2. **Analyze**
   - Advance research, analysis, and modeling capability
3. **Predict**
   - Improve space weather forecast and nowcast capabilities





4. **Transition**
   - Transition capabilities to operational environments
5. **Support**
   - Support robotic and human exploration

6. **Partner**
   - Meet National, International, and societal needs consistent with Government directives

Space Weather Program: Research Implementation

Research-to-Operations-Research (R2O2R)

Annual Solicitation

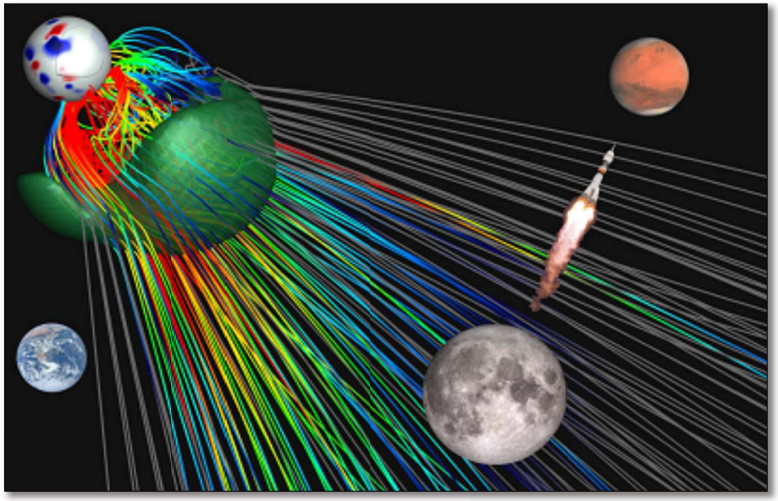
Goal: *To support research that advances scientific understanding while resulting in improved specification and/or forecasting capabilities that are of relevance to NASA space weather priorities and responsive to national space weather needs*

- NASA works with partner agencies to determine the Space Weather ROSES topic each year
- During the review and selection process, NASA meets with partner agencies to discuss proposal recommendations
- Partner agencies have option to fund non-selected proposals

Space Weather Program: Research Implementation

Space Weather Centers of Excellence

The purpose of the Space Weather Centers of Excellence (SWxC) is to provide significant long-term investment in research and infrastructure development to address major challenges in space weather in an integrated multidisciplinary fashion, explicitly and fundamentally incorporating R2O and O2R.



CLEAR Center: All-Clear SEP Prediction

PI: Lulu Zhao, PM: Tamas Gombosi
University of Michigan

CLEAR Center will provide:

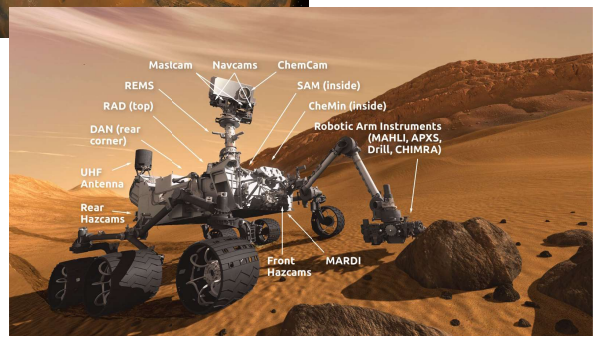
1) Probabilistic forecasts of solar eruptive events
2) Nowcast and forecast the time intensity profiles of energetic particles
3) Predict periods of SEP intensities below preset threshold to issue an all-clear forecast

Space Weather and Exploration

HERMES (Gateway)

MAVEN

RAD (Curiosity)



Address high-priority *Heliophysics science and space weather questions that are best accomplished using a combination of human explorers and robotic systems at the Moon, at Mars, and in deep space.

* Heliophysics exploration topics not limited to Space Weather.

Moon to Mars Strategy: Heliophysics Science

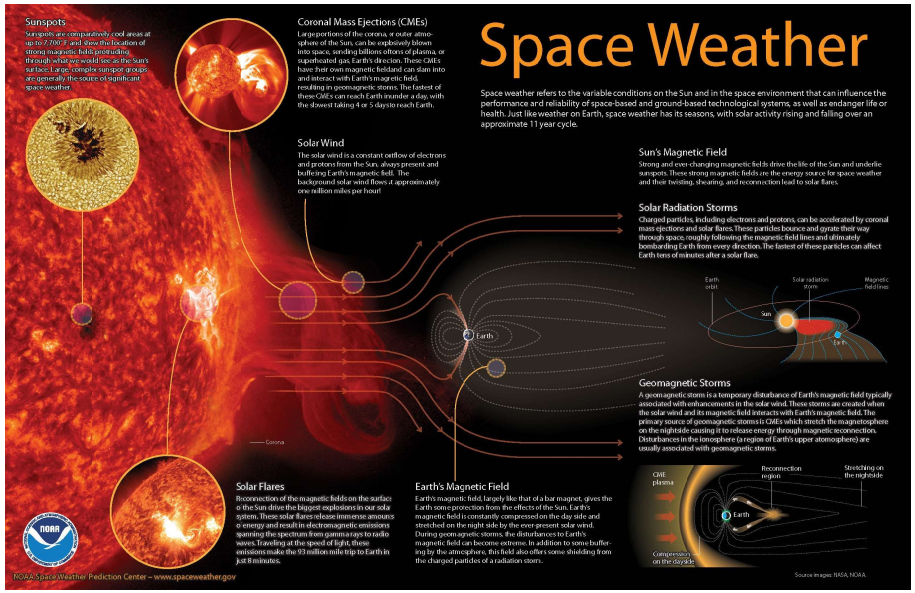


Image credit: NOAA

HS-1 Improve understanding of space weather phenomena to enable enhanced observation and prediction of the dynamic environment from space to the surface at the Moon and Mars.

HS-2 Determine the history of the Sun and solar system as recorded in the lunar and Martian regolith.

HS-3 Investigate and characterize fundamental plasma processes, including dust-plasma interactions, using the cislunar, near-Mars, and surface environments as laboratories.

HS-4 Improve understanding of magnetotail and pristine solar wind dynamics in the vicinity of the Moon and around Mars.

Moon to Mars Strategy: Heliophysics Objectives

Recurring Tenets		
The Recurring Tenets (RTs) capture common themes that are broadly applicable across all of the Moon to Mars objectives and goals.	RT-3	Crew Return: Return crews safely to Earth while mitigating adverse impacts to crew health.
Science-Enabling (SE) Objectives		
Goal: Develop integrated human and robotic methods and advanced techniques that enable high-priority scientific questions to be addressed around and on the Moon and Mars.	SE-1	Provide in-depth, mission-specific science training for astronauts to enable crew to perform high-priority or transformational science on the surface of the Moon, and Mars, and in deep space.
	SE-2	Enable Earth-based scientists to remotely support astronaut surface and deep space activities using advanced techniques and tools.
Applied Science (AS) Objectives		
Goal: Conduct science on the Moon, in cislunar space, and around and on Mars using integrated human and robotic methods and advanced techniques, to inform design and development of exploration systems and enable safe operations.	AS-1	Characterize and monitor the contemporary environments of the lunar and Martian surfaces and orbits, including investigations of micrometeorite flux, atmospheric weather, space weather, space weathering, and dust, to plan, support, and monitor safety of crewed operations in these locations.
	AS-2	Coordinate on-going and future science measurements from orbital and surface platforms to optimize human-led science campaigns on the Moon and Mars.
Lunar Infrastructure (LI) Objectives		
Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.	L1-9	Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robot lunar presence.

Moon to Mars: Space Weather Analysis Office

Mission Statement: The Moon to Mars (M2M) Space Weather Analysis Office conducts real-time space weather assessments to support the development and validation of new capabilities for understanding space weather impacts on NASA robotic missions and human exploration activities.

M2M will work as the proving grounds and testbed for the capabilities that will eventually transition to operational agencies.

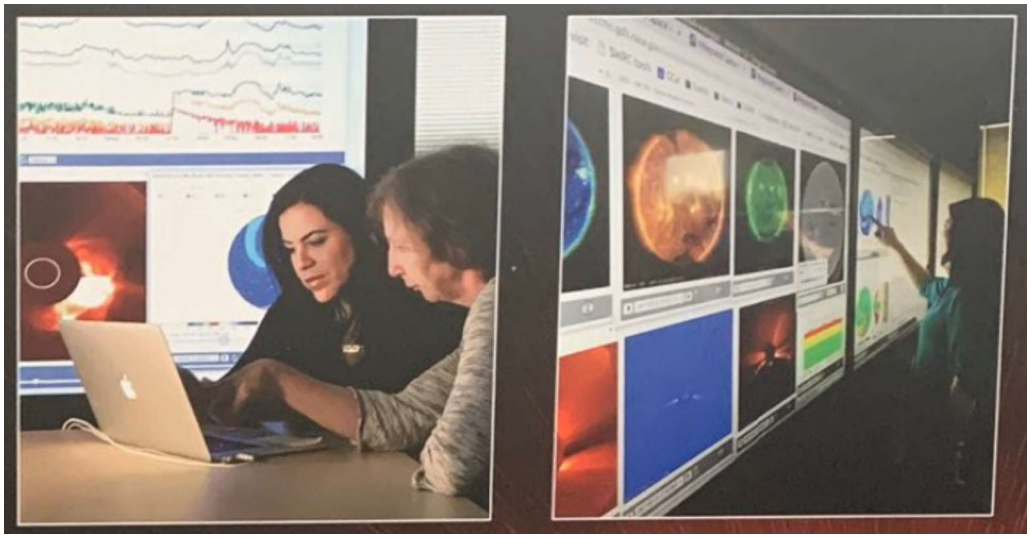


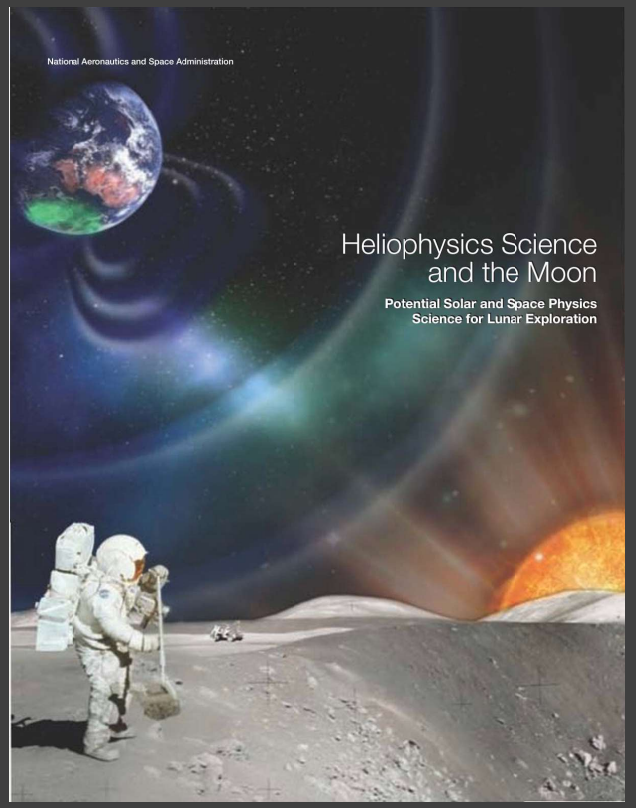
Image credit: NOAA

Heliophysics Science and the Moon**

** Heliophysics science objectives at Mars are under development.

The following example science objectives at the Moon are also relevant to the Mars environs.

Heliophysics Science and the Moon



Potential Solar and Space Physics Science for Lunar Exploration

Report to the NASA Advisory Council Heliophysics Subcommittee
September 2007

https://ntrs.nasa.gov/api/citations/20090010241/downloads/20090010241.pdf

Heliophysics Science and the Moon

Following ***example*** concepts pulled from Decadal community white papers**

Bulletin of the AAS
Vol. 55, Issue 3 (Heliophysics 2024 Decadal Whitepapers)

https://baas.aas.org/vol-55-issue-3

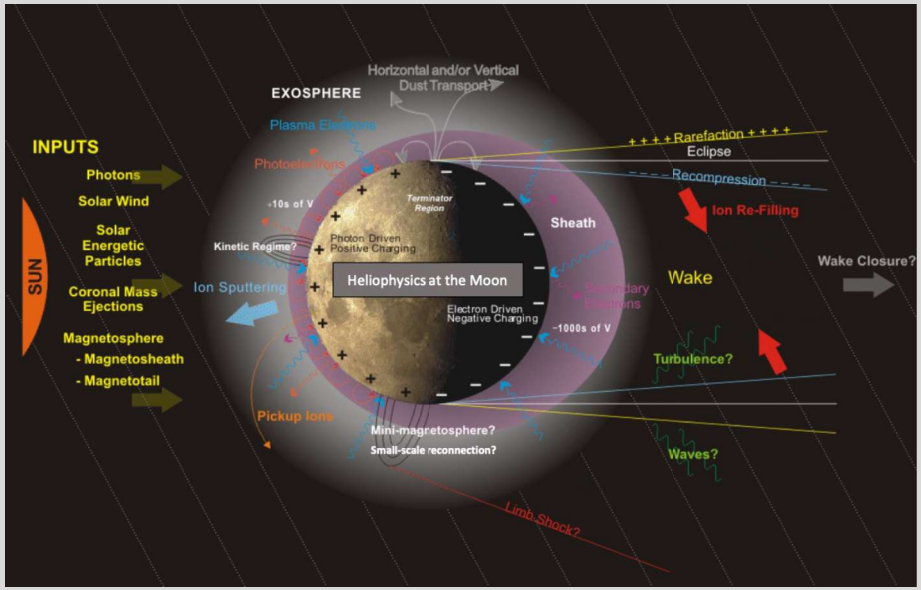
** Descriptions mentioned here do not indicate Decadal endorsement.

Heliophysics Science on the Moon

Fundamental Physics

Increased and sustained access provides an invaluable opportunity to utilize the Moon and cislunar space as a unique Heliophysics laboratory.

- Fundamental research of the radiation and plasma environment:
  - Kinetic plasma physics
  - *In situ* measurements
  - Remote geospace observations



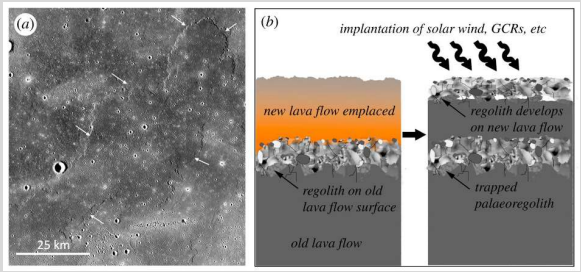
Halekas et al., *The Value of the Moon for Heliophysics,* https://doi.org/10.3847/25c2cfeb.ed6f0be4

Heliophysics Science on the Moon

Lunar Sampling

Cross-disciplinary Opportunity (Helio/Lunar/Planetary)

- Solar activity can be traced chronologically through signatures left on the lunar surface, providing insight into the Sun's evolution (past and future) and its impact on solar system bodies.
- **Key timing:** Coordinated prioritization of diagnostic sample sites and protocols of sample handling enabled by cross-community efforts and repeated/distributed returns to the lunar surface.



Proxy	Meaning	Solar Assumptions	Solar Input
Cosmic Ray Exposure Age	Indicates exposure to cosmic rays (down to several meters)	Assumes a constant flux of GCRs and SEPs over time	SEP/GCR Flux/Spectrum over time, Heliosphere properties that modulate GCR flux/spectra
Particle/Fission Tracks	Indicates irradiation of a particular sample over an integrated time by energetic particles	Varying assumptions about the flux and plausible spectra of input GCRs/SEPs	SEP/GCR Flux/Spectrum over time, Heliosphere properties that modulate GCR flux/spectra
Antiquity Age	Semi-quantifies formation age of a breccia - the time at which a soil is lithified into a breccia	Dependent on isotope ratios normalized to a constant solar wind flux	Overall SEP flux rate from Solar Wind (particularly Argon), Solar UV flux input for ionization
Maturity Index	Indicates surface exposure of particular sample (in top mm of the surface)	Dependent on assumption of constant solar wind particle flux	Solar wind flux rate - isotopes of helium-3, neon-20 and argon-36

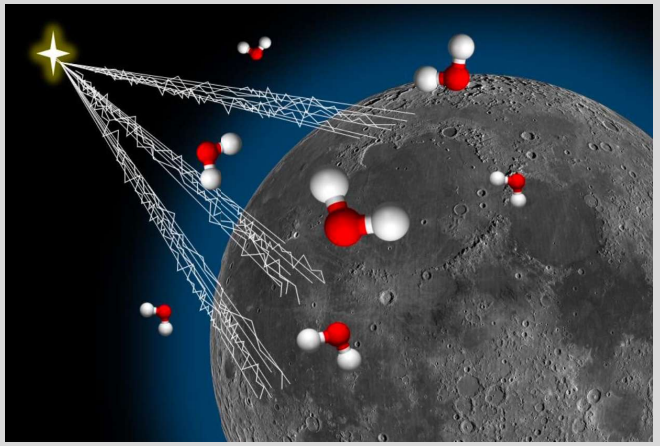
Saxena et al., *Lunar Samples are Time Capsules of the Sun*, https://doi.org/10.3847/25c2cfeb.8e7c5ec9

Heliophysics Science on the Moon

Space Weathering

Space weathering fundamentally variably alters the composition of the lunar regolith and impacts interpretation of surface studies across disciplines. Understanding the effects of space weathering is critical to accurately analyzing surface processes and is applicable to other airless bodies in the solar system.

- Pertinent studies include impacts on volatiles and the regolith as well as the connection to solar energetic particle events.
- Example measurements:
  - SEP and local plasma variability;
  - Space-weathered signatures on localized surfaces/samples relative to the ambient plasma environment;
  - Solar-plasma interactions at the lunar poles (impacts on frozen volatiles)



Ahrens et al., *Space Weathering at the Moon...*, https://doi.org/10.3847/25c2cfeb.4de28fb2

Heliophysics Science on and around the Moon

Maximizing Integration with Artemis

Close partnership between the Heliophysics, Lunar, and Planetary science communities along with the agencies leading the Artemis and beyond missions will ensure remarkable discoveries and feats in science and exploration.

The timing is critical for Heliophysics to remain involved with the Artemis+ architecture requirements planning.

- Heliophysics community integration with CLPS opportunities
- Critical need for high speed Communications Relays
- User input and feedback into forecasting and nowcasting tools
- Forward-thinking on missions to the lunar surface, Gateway (external, internal, logistics modules, cubesats, etc.), deep-space transit, and Mars

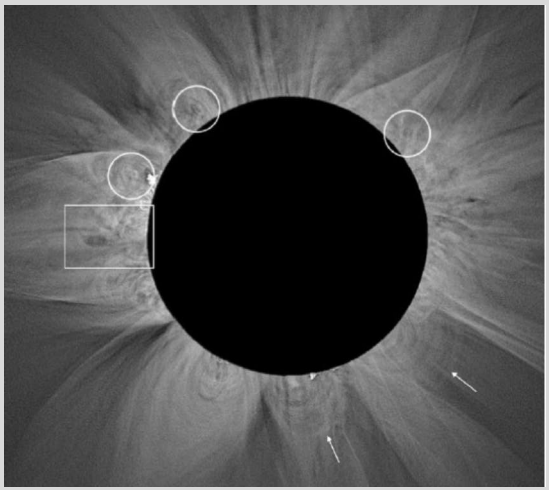
Halford et al., *Artemis, Gateway, the return to the Moon and forward to Mars for Heliophysics,* https://doi.org/10.3847/25c2cfeb.497f482a

Heliophysics Science around the Moon

Advantages of Cislunar Observations

Cislunar space offers a unique Heliophysics perspective of the Moon, Sun, and Geospace.

- Earth-directed observations from the Moon allow for monitoring the impacts of space weather on the magnetosphere.
- Sun-directed remote observations provide an opportunity for testing mission-enabling/enhancing data streams immediately accessible to astronauts.
- The Moon can be used as occulter for coronal studies that are typically only accessible through short-duration, sporadic eclipses.
- Favorable vantage point for accessing the *in situ* solar wind from both protected and deep space environments.



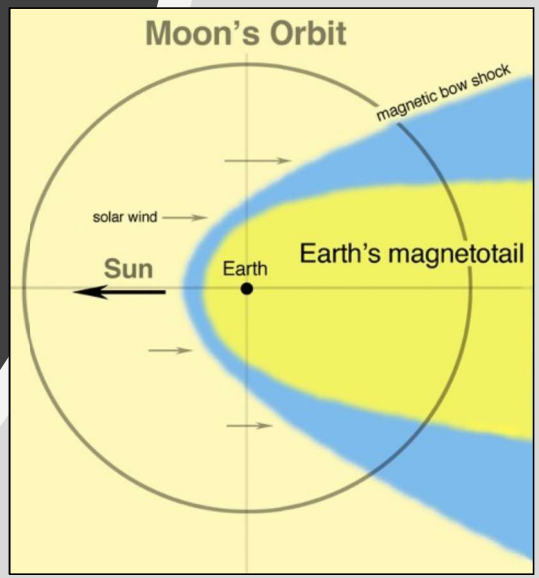
Cooper et al., *Heliophysics from, by, and of the Moon in the Age of Artemis...*, https://doi.org/10.3847/25c2cfeb.beac35c4

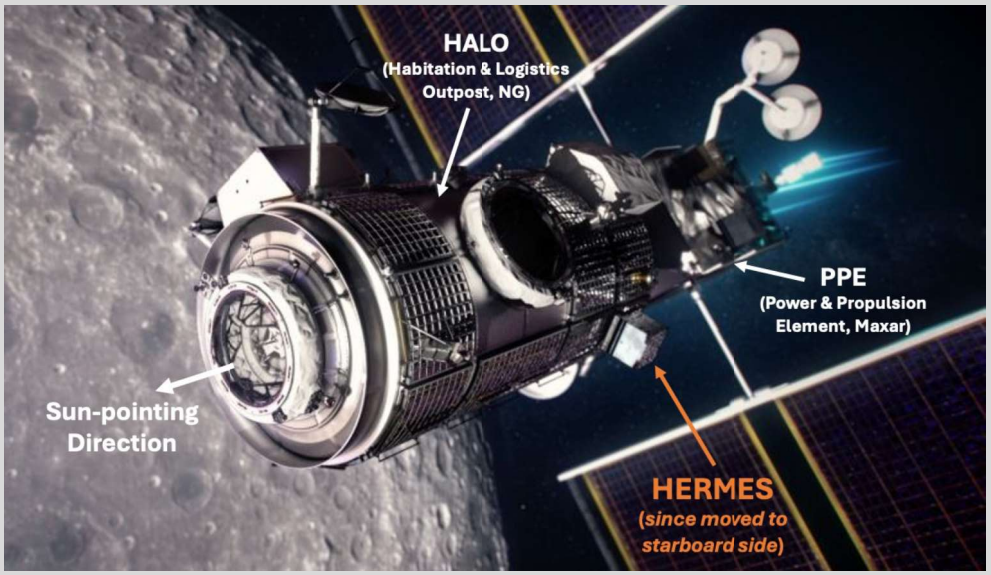
Heliophysics Science around the Moon

HERMES

NASA's First Science Payload on Gateway

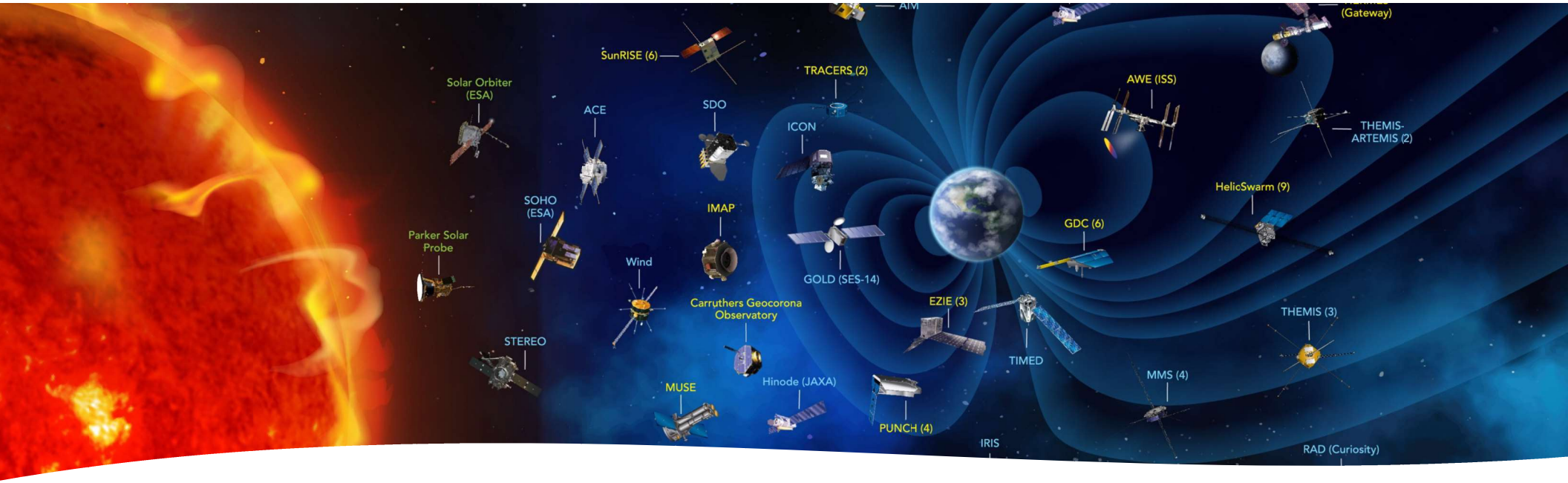
- External, will launch manifested on the HALO
- Suite of particles and fields measurements for analyzing the solar wind environment in and out of the magnetosphere
- Pathfinder for mission-enabling/enhancing space weather payloads
- Complementary payloads included with manifest: ERSA (ESA) & IDA (ESA/JAXA)





Paterson et al., *The HERMES Payload for Gateway: Heliophysics from Lunar Orbit*, https://www.swpc.noaa.gov/sites/default/files/images/u97/Space%20Weather%20Workshop%202023%20-%20Paterson%2018%20Apr.pptx_.pdf

Looking Ahead



Key timing for community inputs

- Updates to vision, strategy, and implementation plans in work.
  - Decadal (~ Fall 2024)
  - Plans for community engagement (RFI/workshop) for input into topics enabled by and supporting deep space exploration:
    - science questions (Heliophysics / space weather)
    - operational support
    - space weather payloads.

- Anticipating future research solicitations through the SWxP.