The Lunar Dust & Plasma Environment:
Decadal-Level Science in the Artemis Era

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Artemis ≠ ARTEMIS

Artemis

US human-exploration program

Successor to 60s-70s Apollo program

Artemis I launched in 2022, Artemis II scheduled for 2026

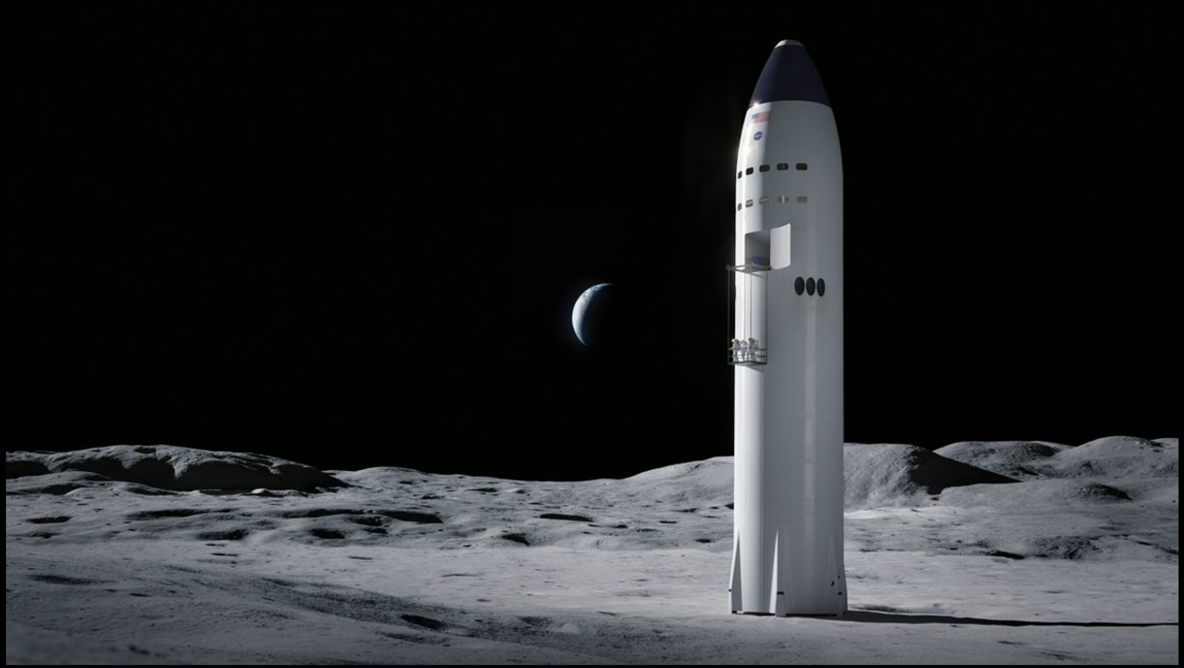
ARTEMIS (or THEMIS-ARTEMIS)

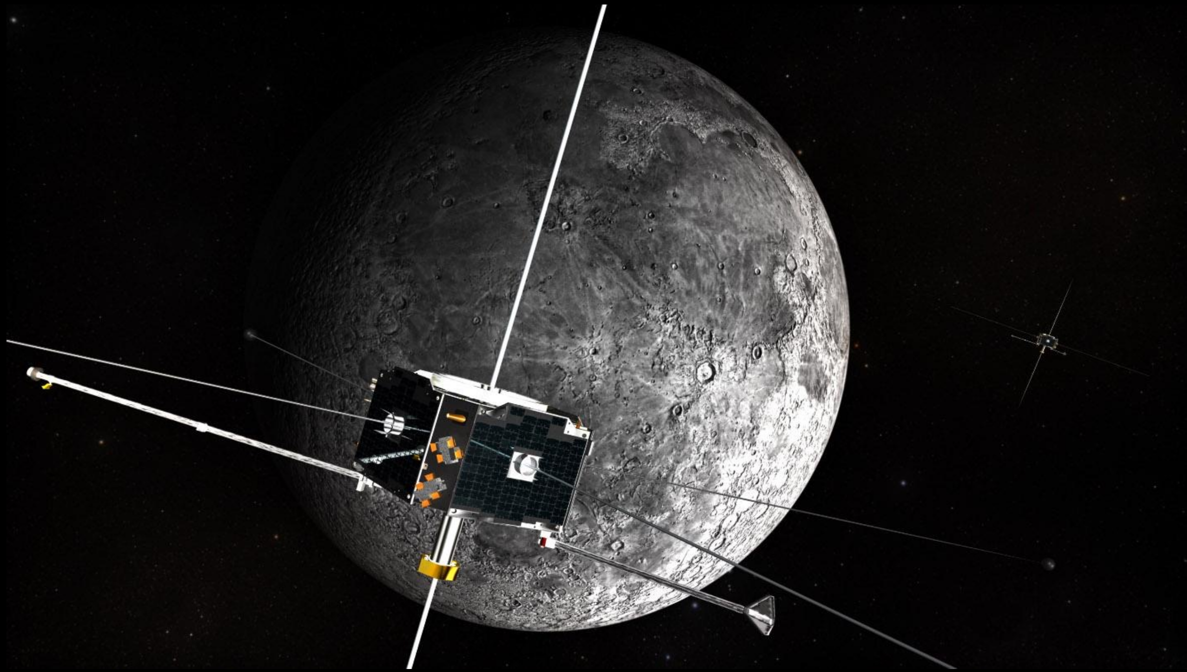
Dual-probe unmanned Heliophysics scientific mission

Launched in 2007 as part of *THEMIS* constellation

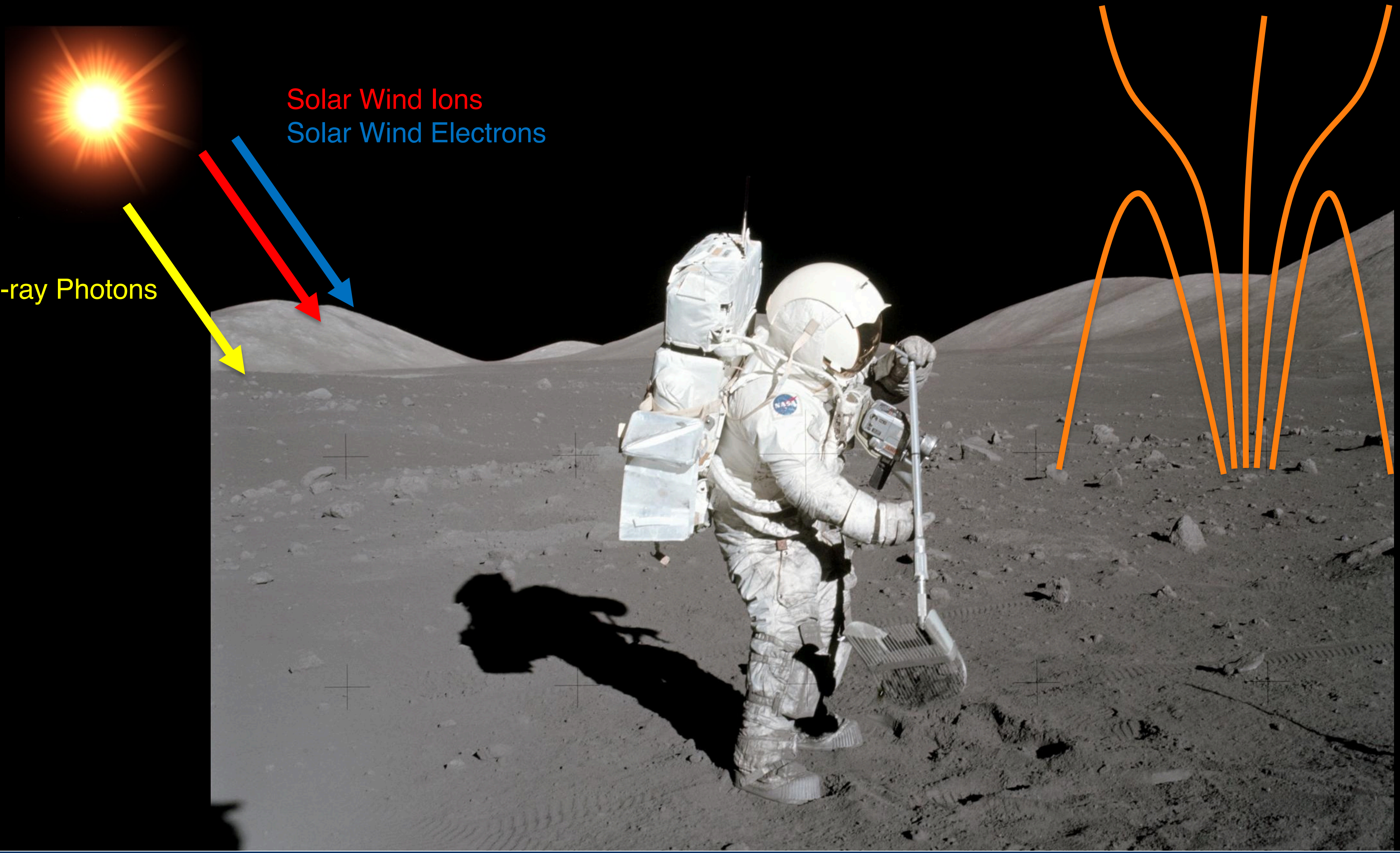
Redirected to lunar orbit in 2010-11

Still operating and returning *loads* of data



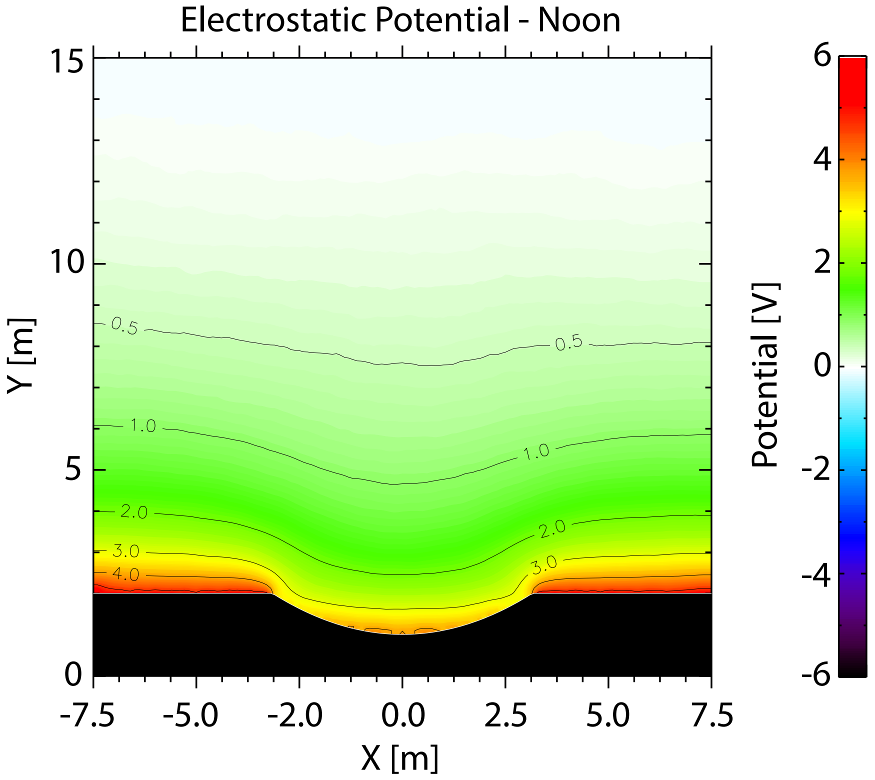


The Lunar Surface Dust and Plasma Environment



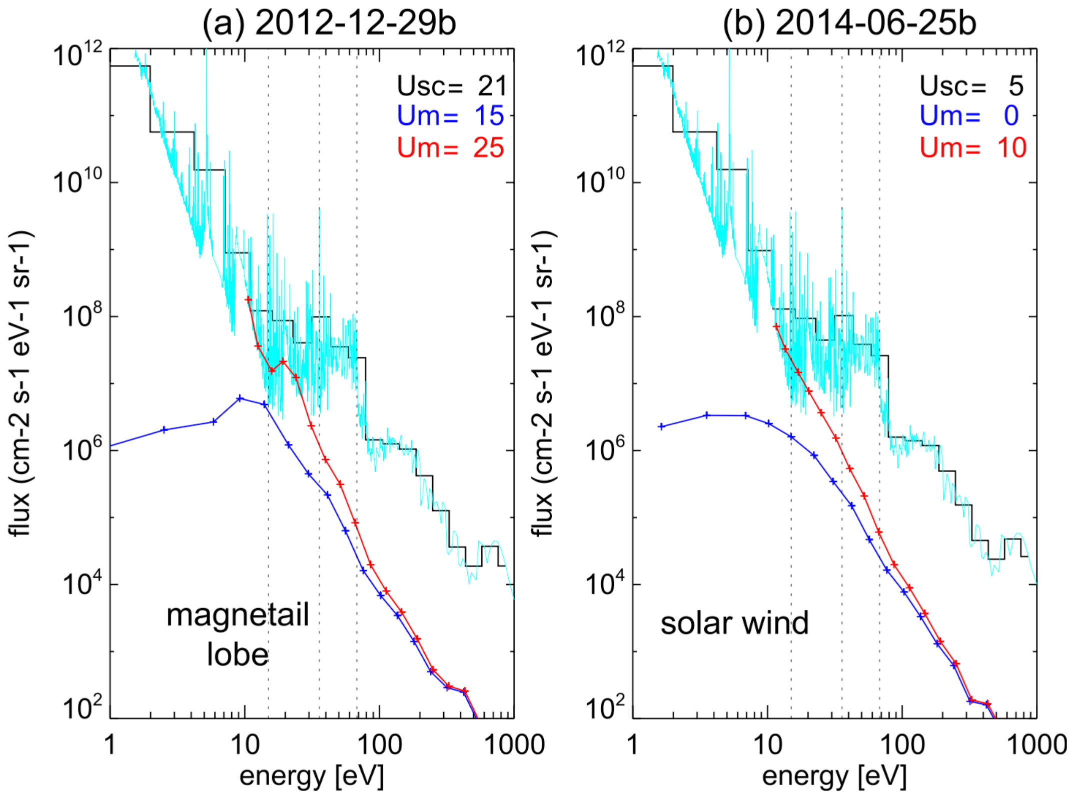
Lunar Plasma Environment: *At the Surface*

Near-surface Scales (meters – tens of meters)
Photoelectron sheath-dominated



Poppe et al., *Icarus*, 2012
See also: Piquette and Horányi, *Icarus*, 2017

Fundamental Physics of Photoemission from Solid Surfaces



Xu et al., *JGR Planets*, 2021

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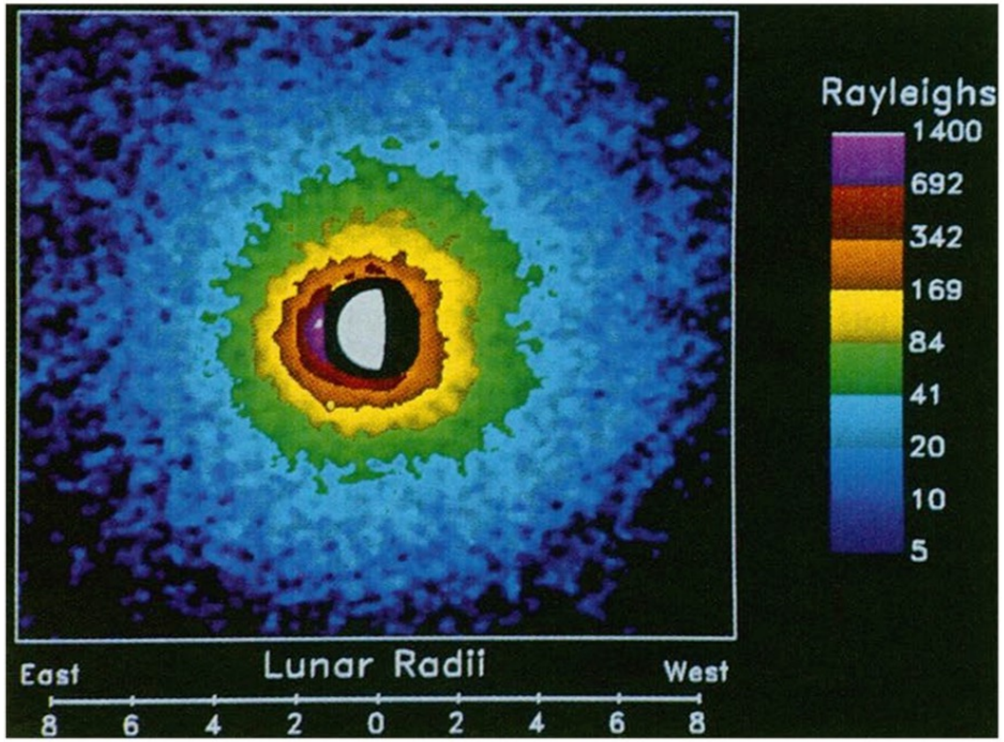
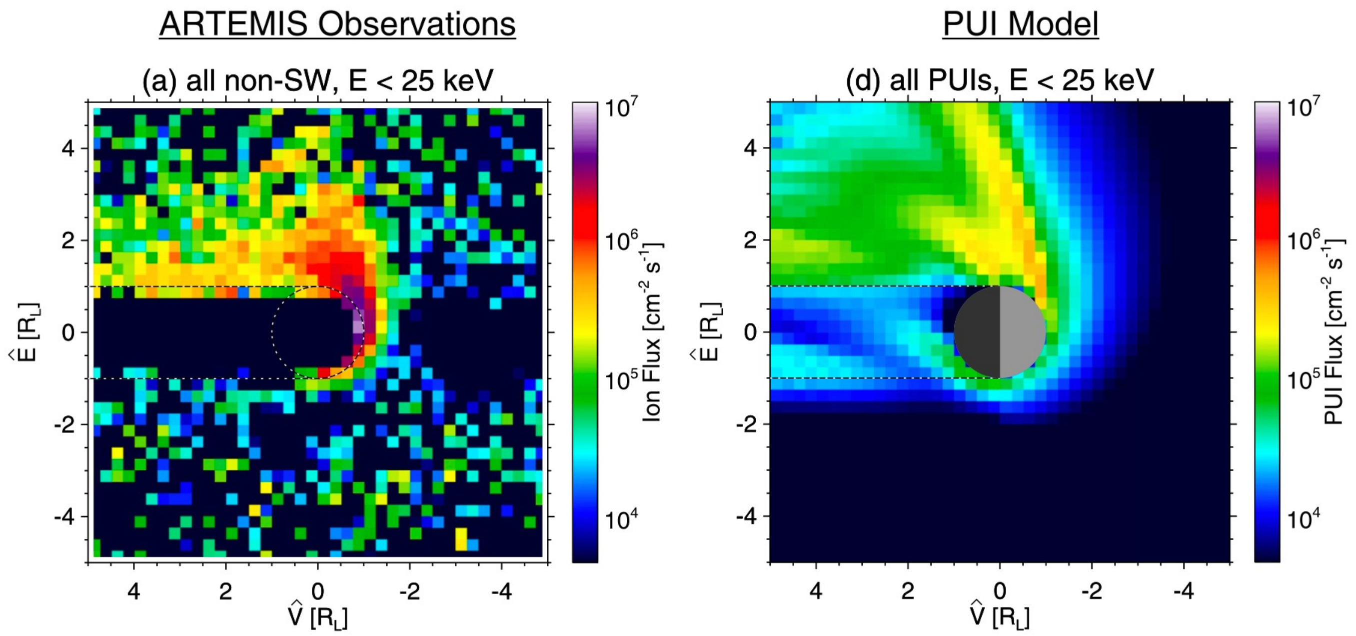
Lunar Plasma Environment: *At Altitude*

Tenuous Neutral Exosphere
Dozens of Neutral Species with Varying Distributions



Flynn and Mendillo, *Science*, 1993

High-altitude Scales (hundreds of km to tens of R_L)
Exospheric Pickup Ion / Reflected Proton-dominated



Poppe et al., *JGR Planets*, 2022

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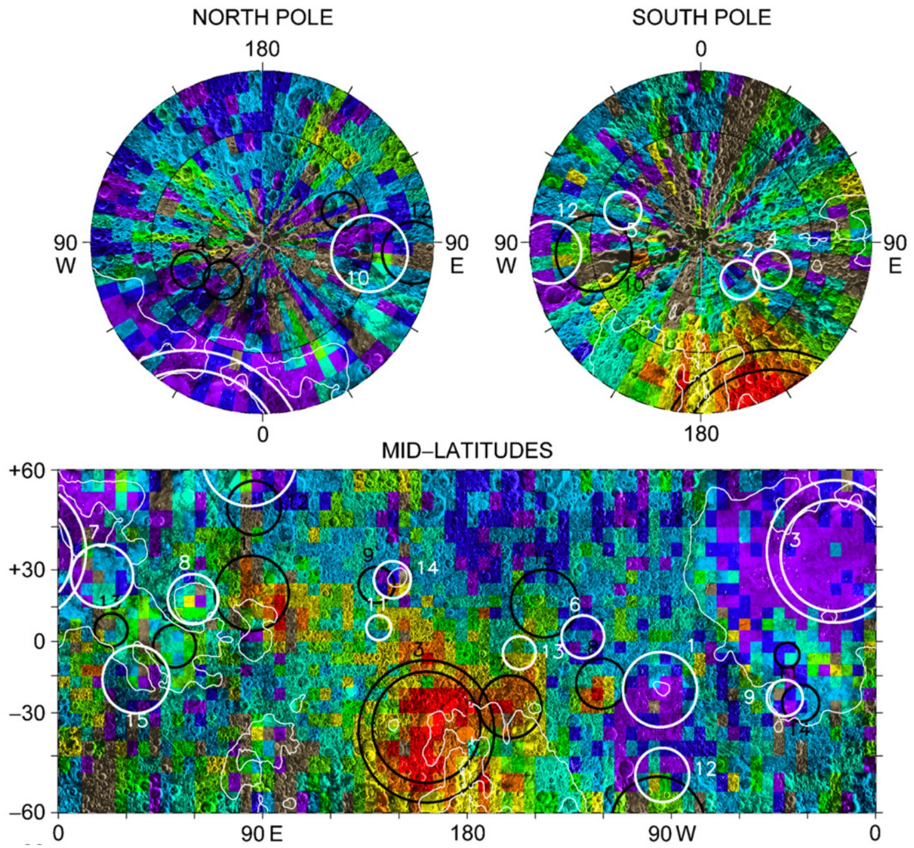
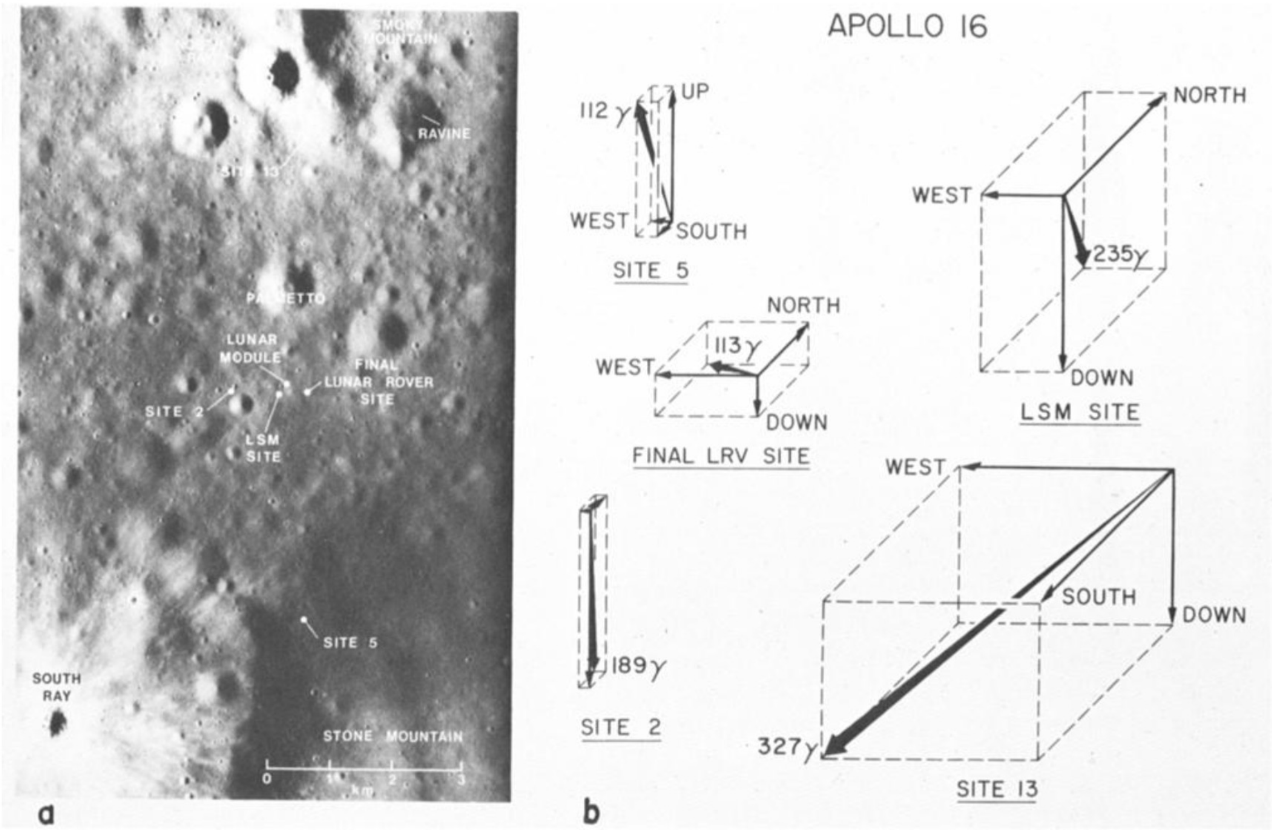
Crustal Magnetization: *A Key Complicating Factor*

Heterogeneous Distributions of Crustal Magnetism at **Global** Scales



Mitchell et al., 2008

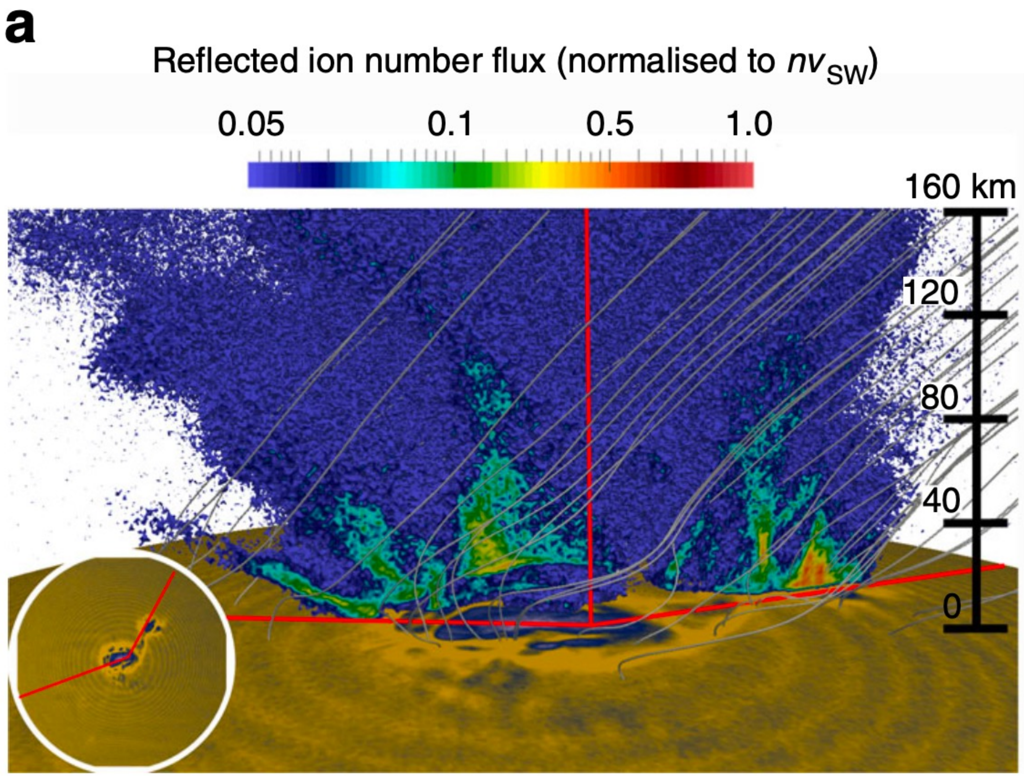
Heterogeneous Distributions of Crustal Magnetism at **Local** Scales



Dyal et al., 1974

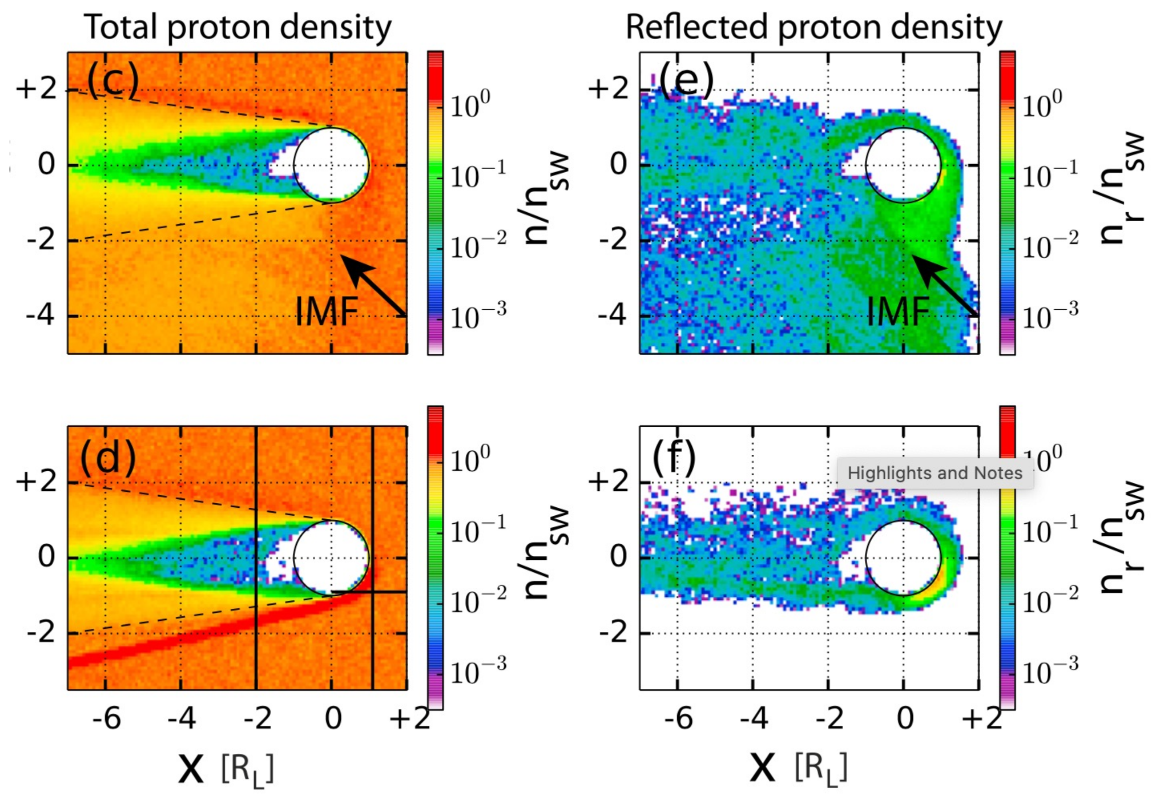
Crustal Magnetization: *A Key Complicating Factor*

Simulations Predict Significant Alteration of the Near-Surface Plasma Environment



Deca et al., 2018

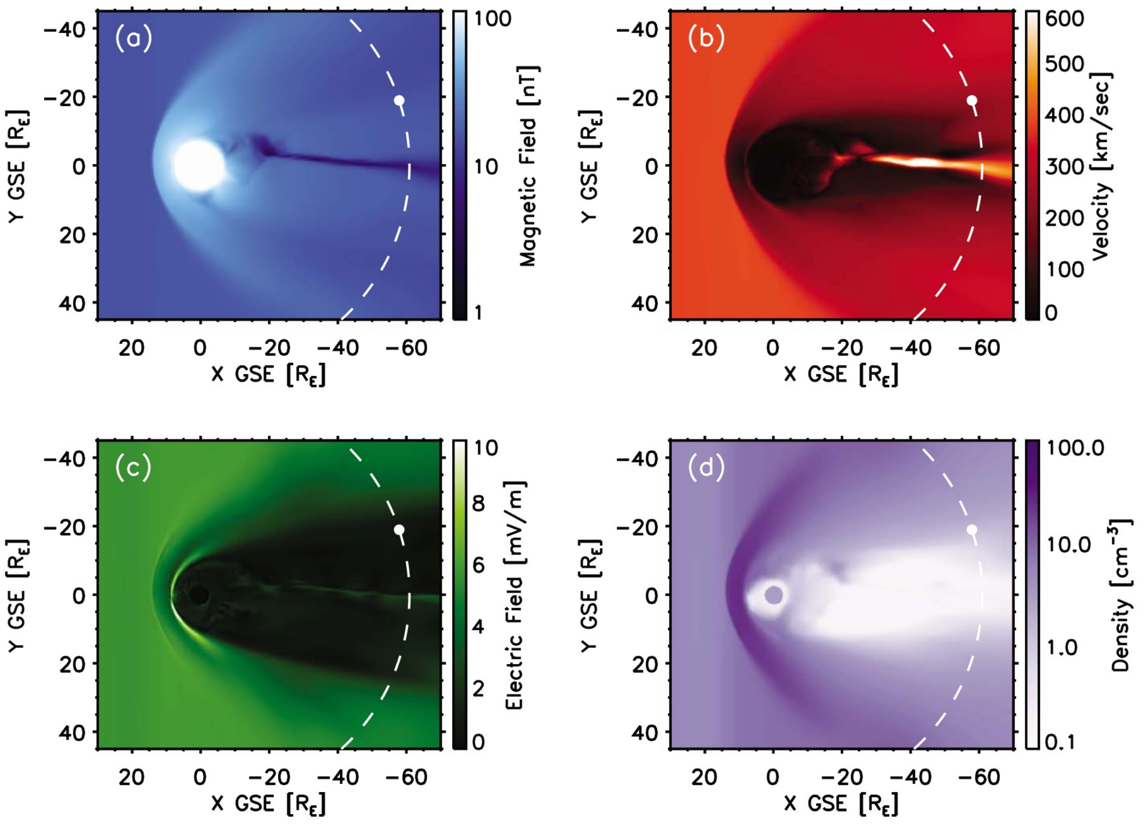
Reflected Ion Species Alter the Regional and Global Plasma Interaction of the Moon



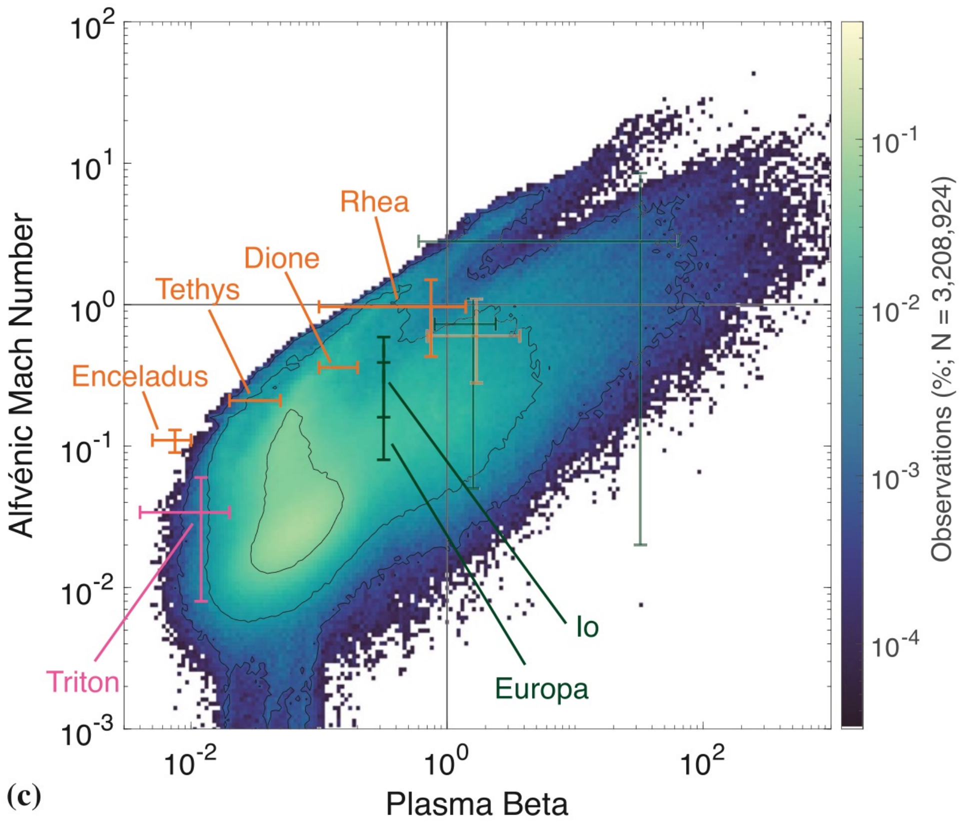
Fatemi et al., 2014

Crossing The Earth's Magnetotail: *A Source of Variability*

Terrestrial magnetotail crossings:
a dynamic plasma environment with connections to outer planet moon-magnetosphere conditions



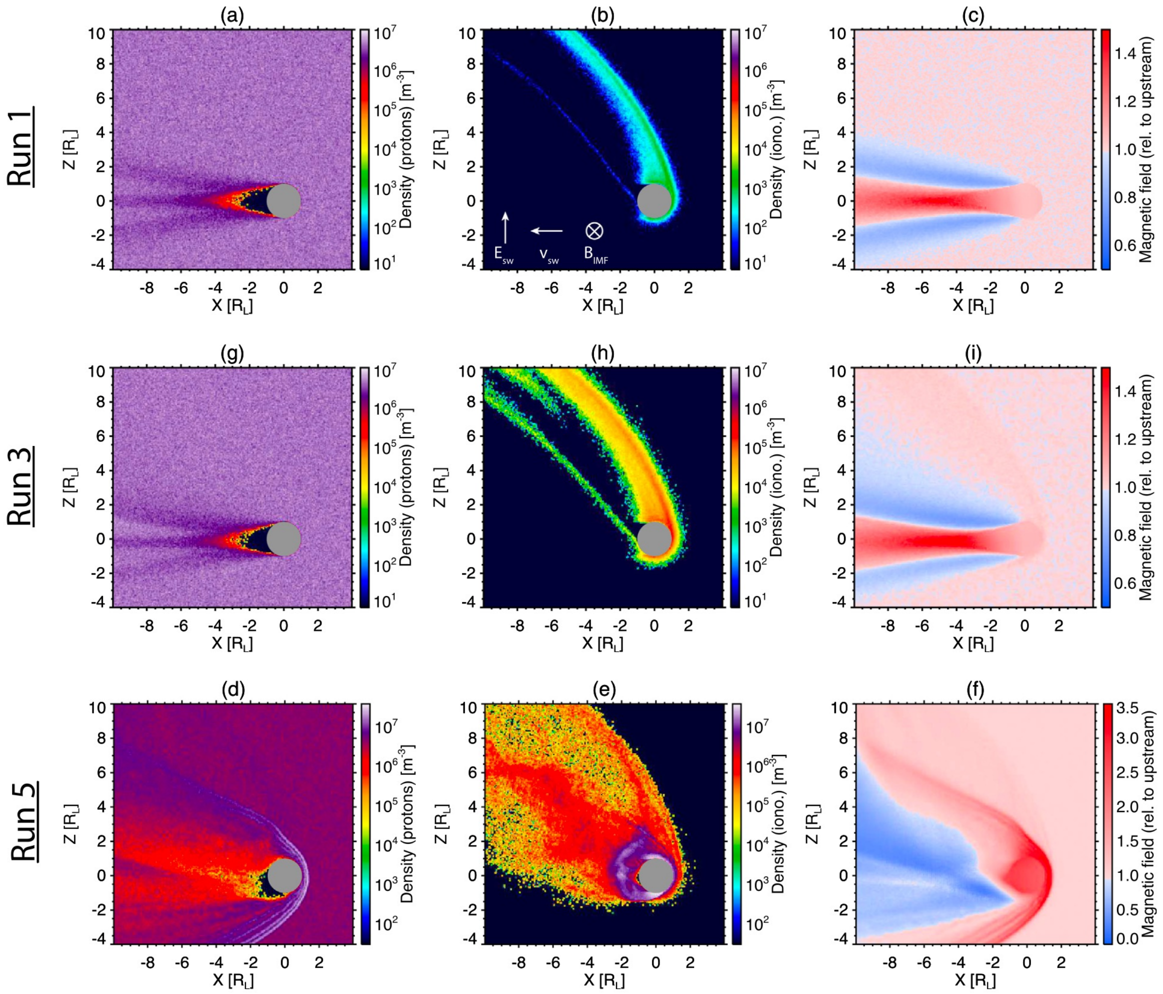
Poppe et al., *GRL*, 2016



Liuzzo et al., *JGR Space Physics*, 2022

Potential Anthropogenic Influences

As humans return to the Moon, significant levels of outgassing may fundamentally alter the lunar plasma interaction



'Native' lunar exosphere & plasma interaction

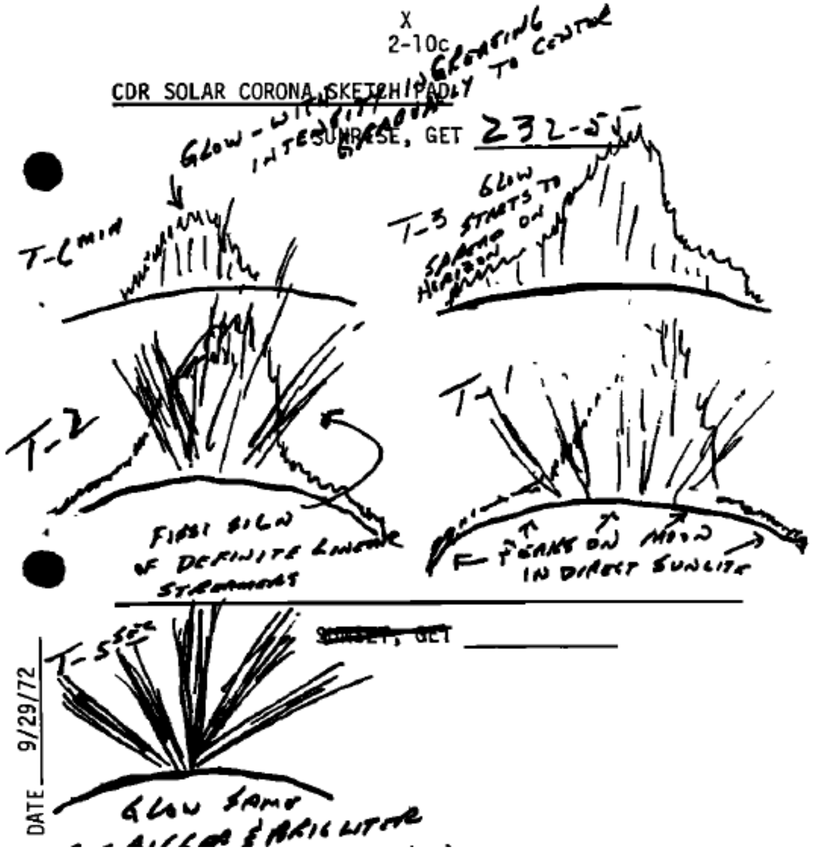
Fully loaded HLS landing

Repeated HLS landings (faster than exospheric decay timescales)

Poppe et al., 2024

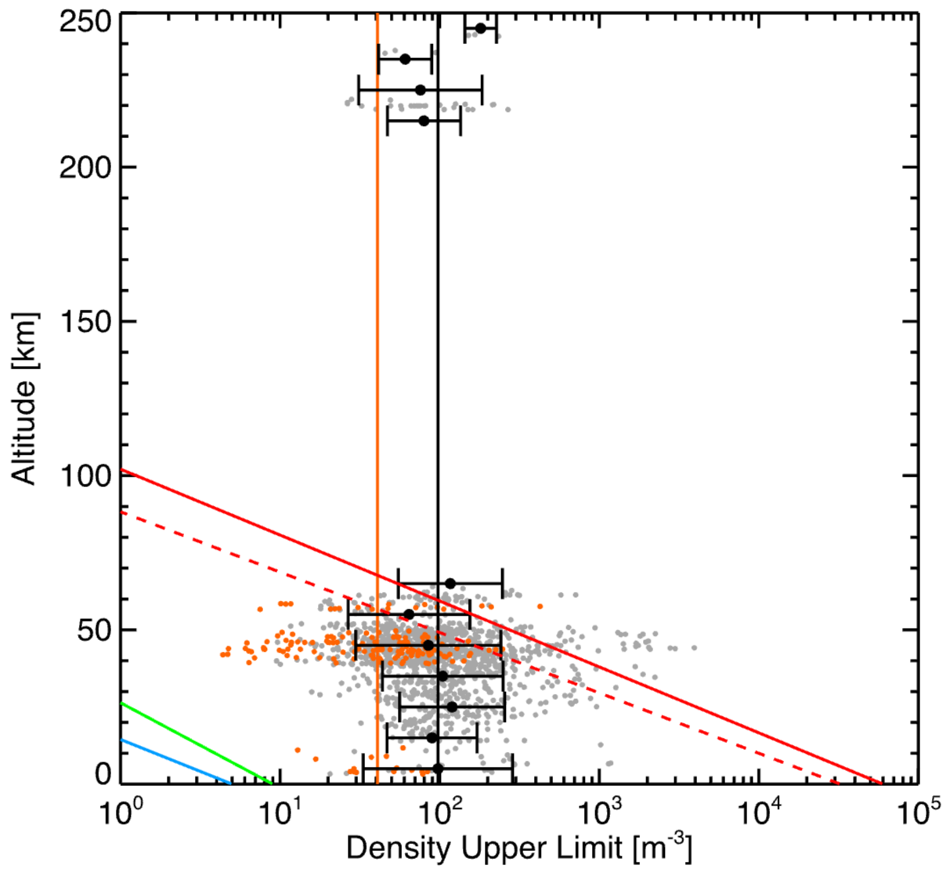
Lunar Dust Observations: *Conflicting Reports at km-scales*

Evidence for High-Altitude (Dust?) Streamers
(Apollo 17 astronaut E. A. Cernan's sketches)



McCoy and Criswell, 1974

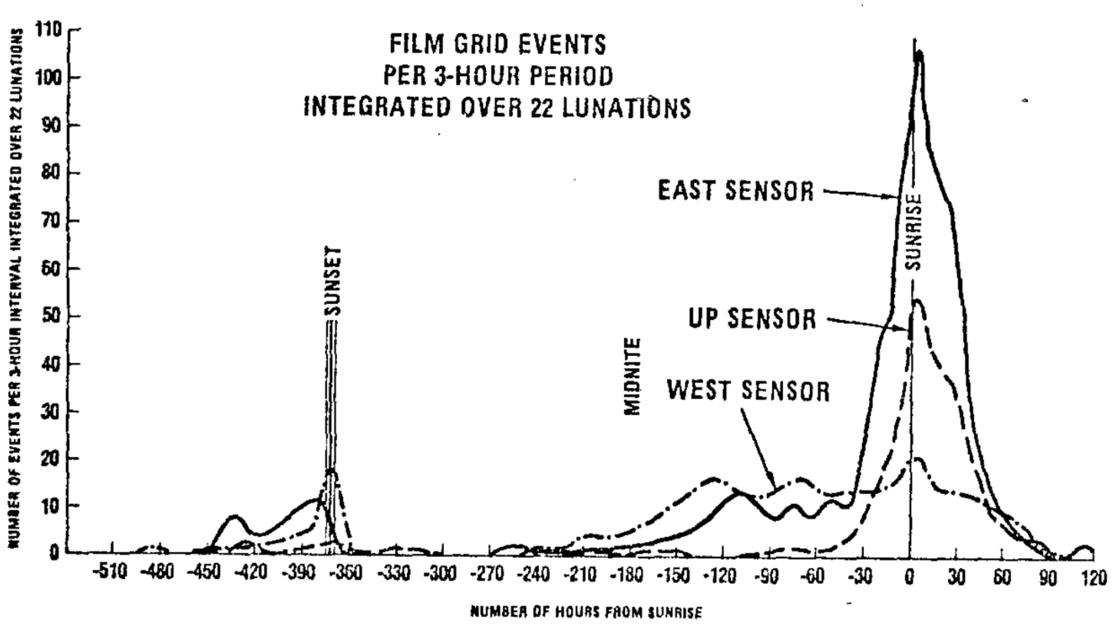
No Evidence for High-Altitude Dust
In-situ Lofted Dust Measurements by LADEE



Szalay and Horányi, 2015

Lunar Dust Observations: *Observations at the Surface*

Evidence for Surface Electrostatic Dust Transport
(Apollo 17 LEAM Experiment)



Berg et al., 1974, 1976

NEED MODERN-DAY MEASUREMENTS!

Big Outstanding Questions

- What is the **near-surface plasma environment** and how does it vary by surface location, lunar phase, local time, and upstream plasma conditions?
- What is the degree of **near-surface dust mobilization**, and how does it vary by surface location, lunar phase, solar and terrestrial conditions, and upstream plasma conditions?
- What are the distributions of **crustal magnetic field strength and direction** at the surface, and how does this influence the local plasma environment?
- How does **the Moon's passage through the terrestrial magnetotail** alter the near-surface plasma and dust environment?
- How does **human activity on the lunar surface** alter the neutral and/or plasma environment of the Moon? How does such activity alter the near-surface dust environment?

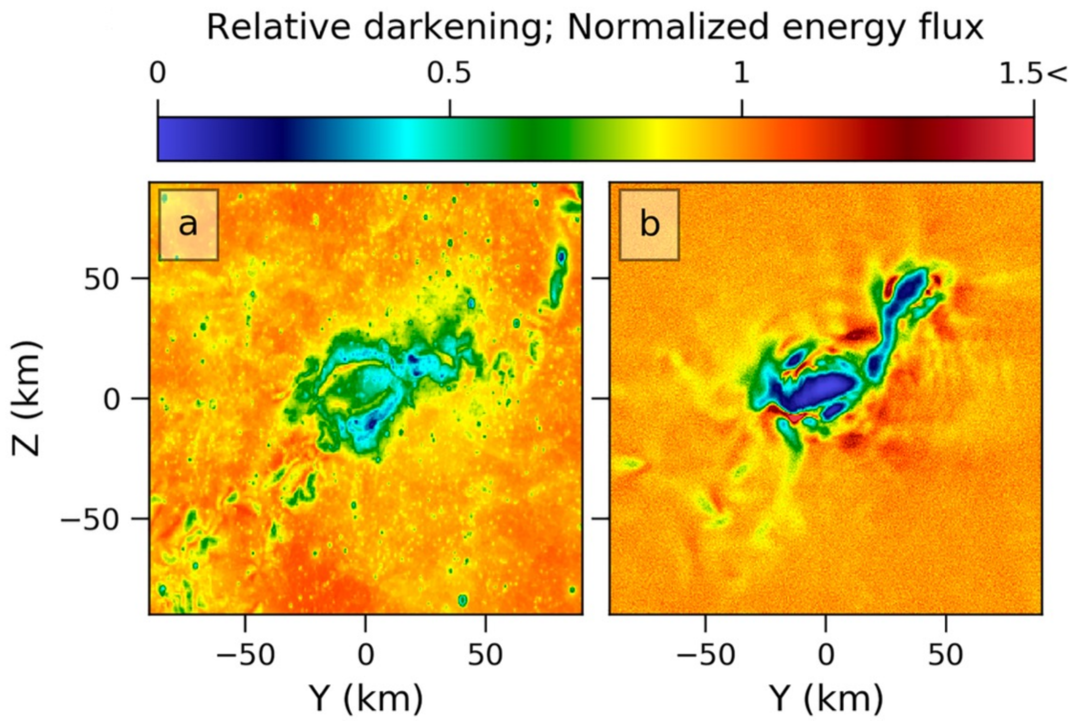
Planned and Conceptual Measurements

Crustal Magnetization: *Upcoming In-situ Measurements*

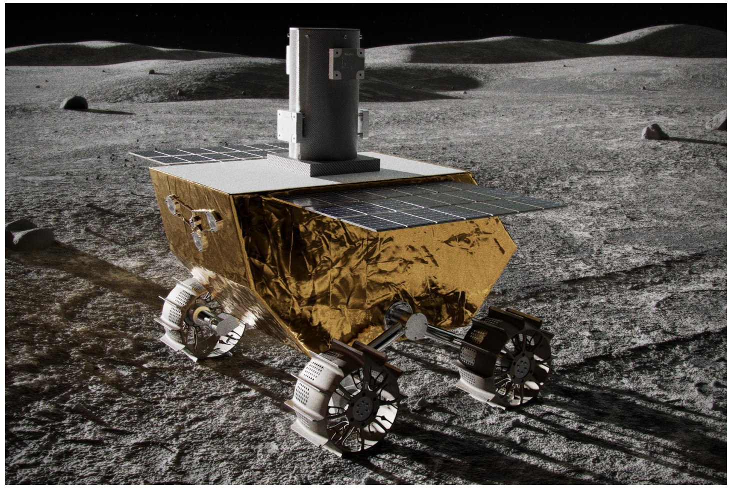
Lunar Vertex Mission

Will explore the plasma and magnetic field environment of the Reiner Gamma magnetic anomaly & “swirl”

Scheduled for flight in “early 2026” (PI Blewett @ APL, DPI Halekas @ UIowa)



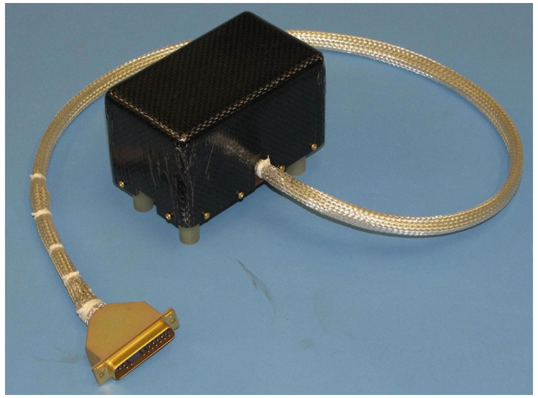
Deca et al., *JGR Planets*, 2020



Surface Plasma Environment: *Conceptual Measurements*

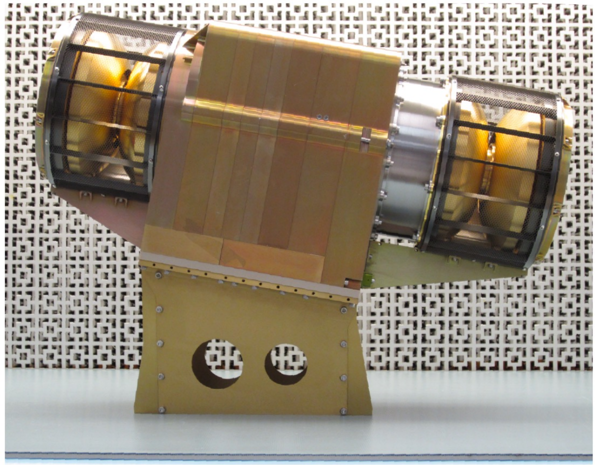
Need for a "Standard" Space Plasma/Space Weather Monitoring Package for the Lunar Surface

Magnetometer



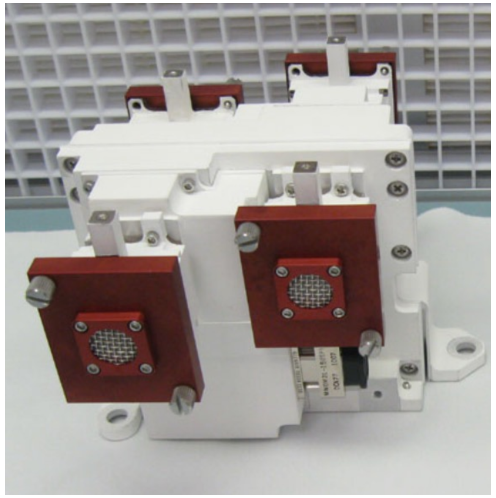
MAVEN

Ion/Electron Spectrometers



Parker Solar Probe

Energetic Particle Spectrometer



THEMIS, ARTEMIS, MAVEN

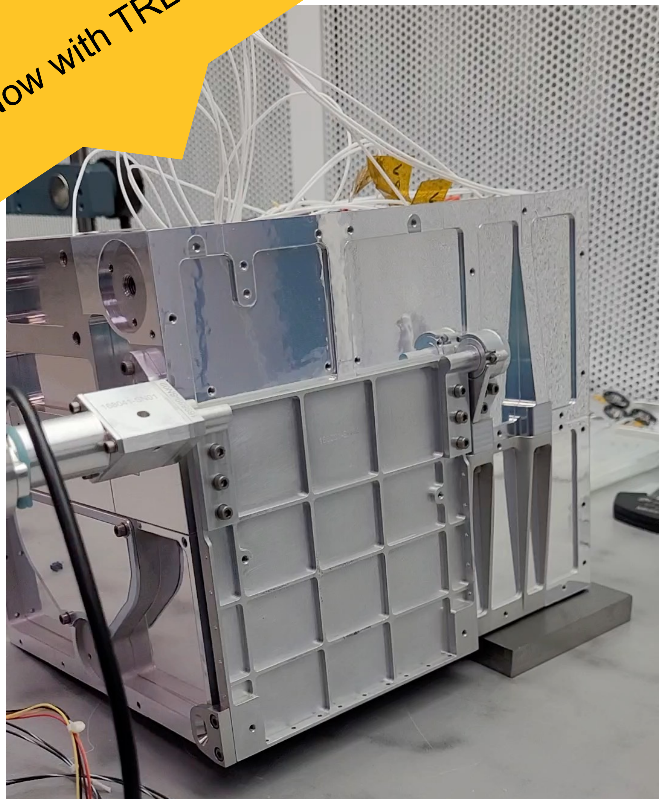
Langmuir Probe

MAVEN

Lunar Dust Observations: *Potential Surface Instrument*

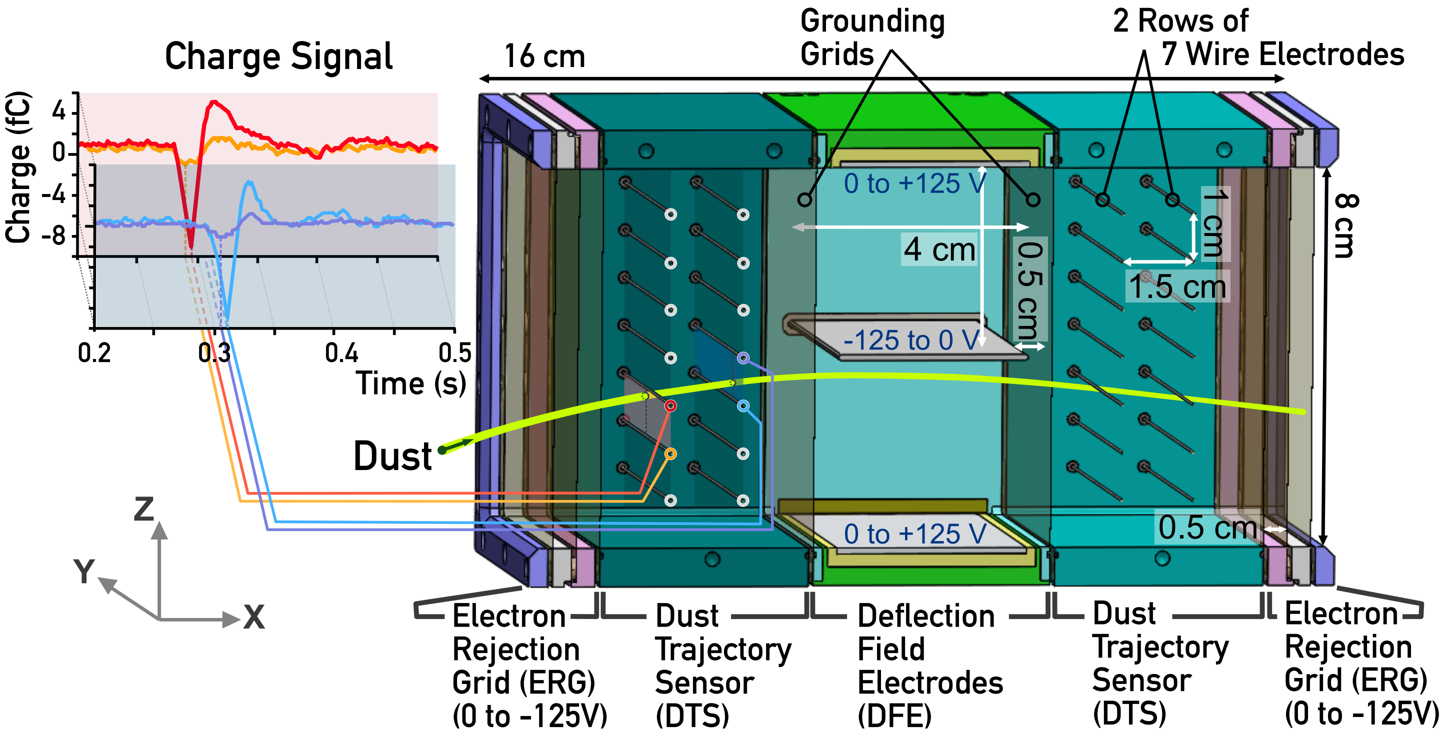
PI: X. Wang, Univ. Colorado

Now with TRL 6!



Electrostatic Dust Analyzer (EDA)

(NASA DALI Program, Univ. Colorado Boulder)



Measure the charge, velocity, mass (size), and flux of lofted lunar dust

Wang et al., 2024

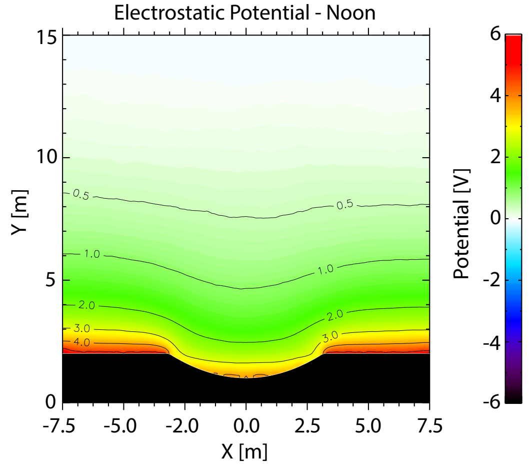
Summary

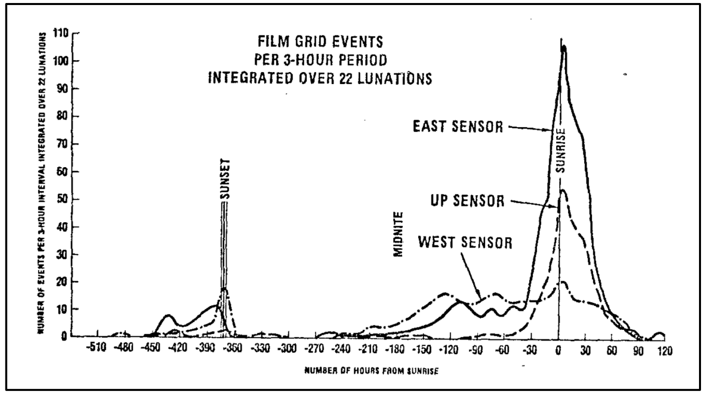
- **Lunar plasma environment:**
  - *Complex and spatially variable, driven by both ambient plasmas and surface properties*

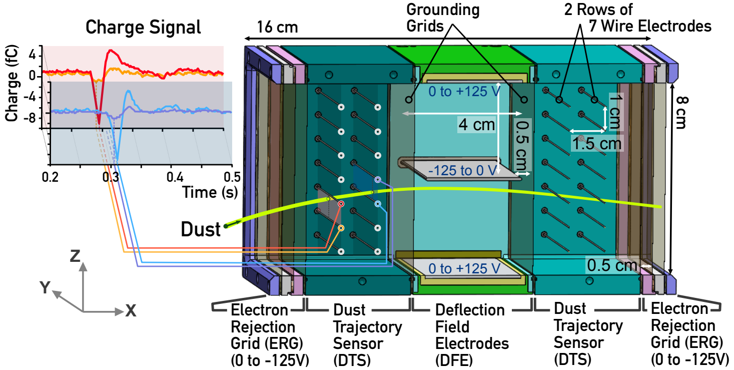
- **Lunar dust environment:**
  - *Dust mobilization is likely, but significant uncertainty remains in its geophysical characteristics*

- **Future measurements:**
  - *Clear need for a ‘standard’ space plasma/space weather package to deploy on the lunar surface*

  - *Clear need for modern-day in-situ dust dynamics measurements*







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Backup Slides

Notes

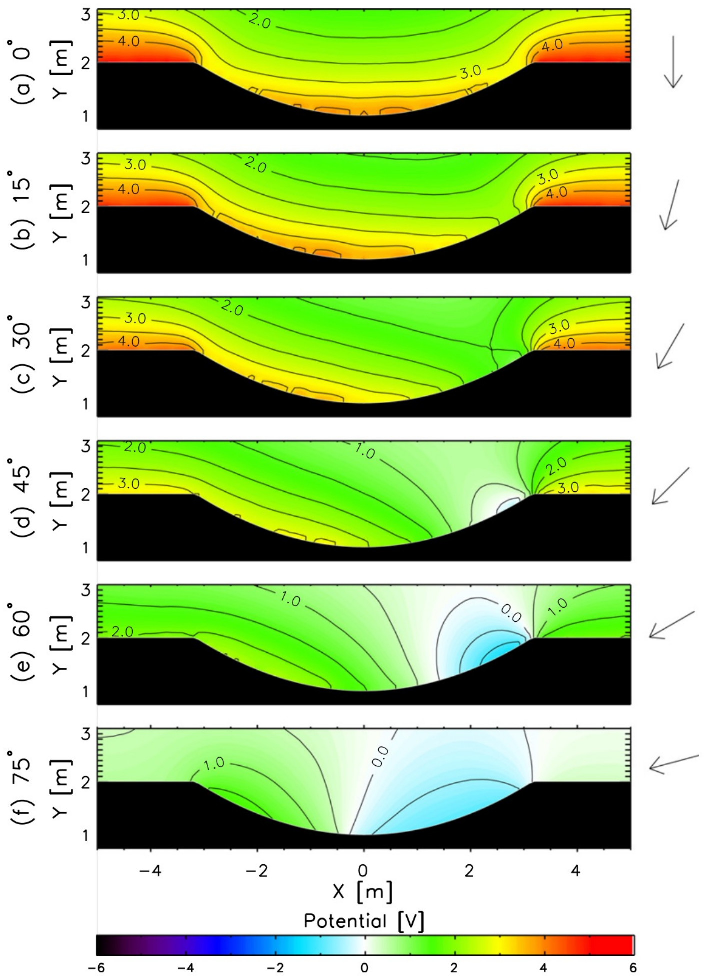
The Panel on Heliophysics, Physics, and Physical Science will gather information and identify and articulate the science objectives related to solar physics, space weather, astronomy, and fundamental physics that would be most enabled by human explorers on the moon. Using NASA's 2022 Moon to Mars Objectives, the National Academies reports *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, *Thriving in Space: Ensuring the Future of Biological and Physical Sciences Research: A Decadal Survey for 2023-2032* and *The Next Decade of Discovery in Solar and Space Physics: Exploring and Safeguarding Humanity's Home in Space*, and other gathered information, the panel will:

- Identify key science objectives within solar physics, space weather, astronomy, and fundamental physics that can or must be done by human explorers on the lunar surface;
- Specify the key measurements, either in situ or via returned samples, needed to achieve these key science objectives and why human explorers would enable those measurements (as opposed to robotic assets);
- Detail any pre-placed assets (e.g., tools, mobility devices, robotic hardware, and equipment delivered to the lunar surface prior to human landing) that would be either necessary or enabling of these key measurements; and
- 4. Prioritize potential non-polar landing sites or characteristics of landing sites that would be most enabling of these key science objectives and measurements

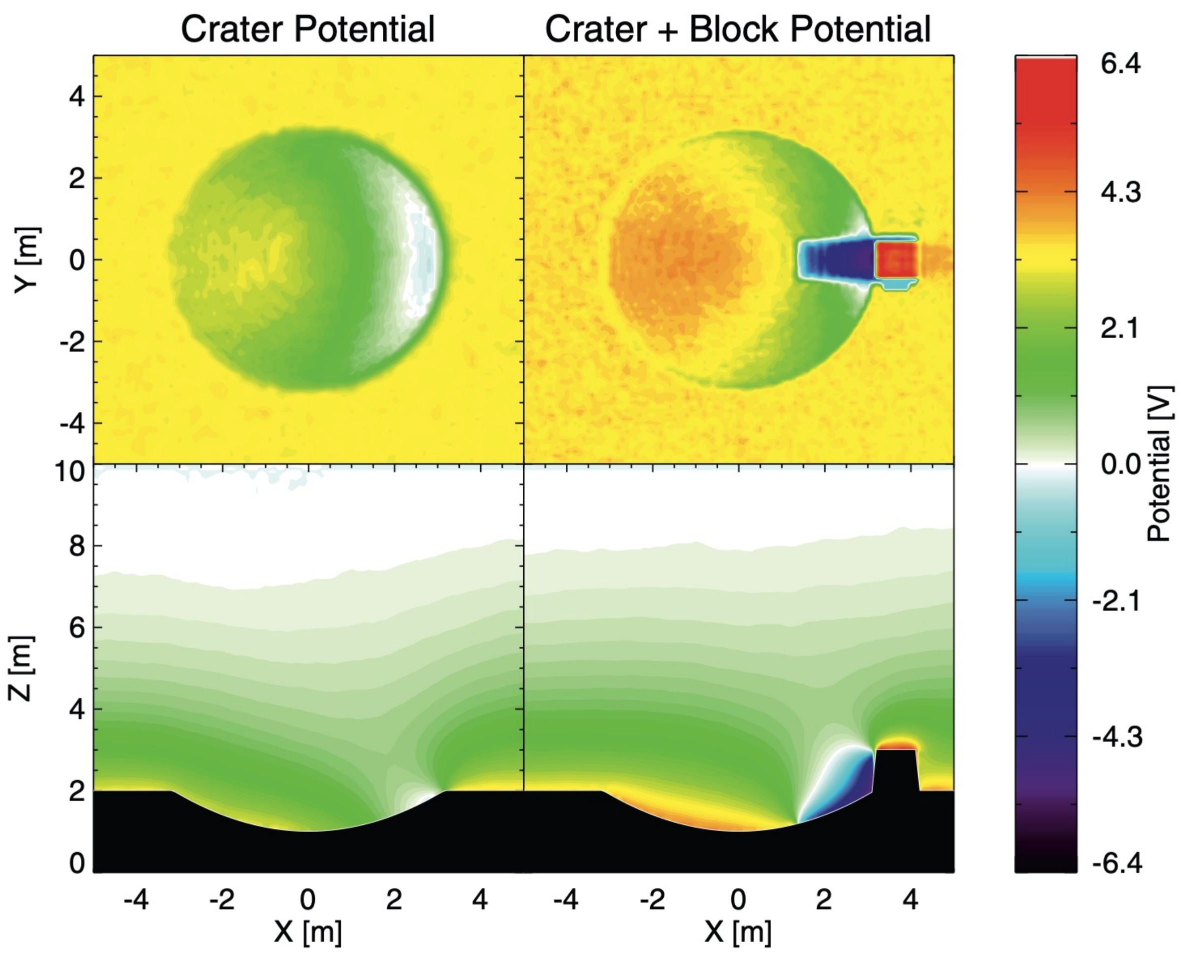
This panel is one of four operating under the aegis of "Key Non-Polar Destinations Across the Moon to Address Decadal-level Science Objectives with Human Explorers" and its steering committee. The panel will provide the steering committee with its findings and a science traceability matrix outlining each potential non-polar landing site (or characteristics of landing sites) and the science objectives it would enable. The panel will not produce recommendations as part of its input to the project's Steering Committee.

- For each target destination identified, provide
  - Key science objectives to be addressed at that location, tied to the National Academies report *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032* (OWL) and NASA's Moon to Mars Objectives.
  - Key measurements, made in situ, needed to achieve the identified science objectives.
  - Key measurements that can or must be enabled via samples collected and returned to terrestrial labs to achieve the identified science objectives
  - Justification for why these measurements or sample collection efforts would require or would most effectively be enabled by human explorers (as opposed to robotic rovers or sample return)
  - Discussion of what, if any, pre-placed assets would be necessary or enabling to accomplish these measurements (e.g., tools, mobility devices, robotic hardware, and equipment delivered to the lunar surface prior to human landing)
  - Key resources available at this destination that might be useful for in-situ resource utilization.

Lunar Plasma Environments: Near-surface PIC Modeling



Poppe et al., *Icarus*, 2012



Piquette and Horányi, *Icarus*, 2017

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