The Moon's plasma environment in 2023:
Compelling science with much more to come!

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Dust, Atmosphere, and Plasma Environment of the Moon & Small Bodies

With thanks to:
L. Liuzzo, S. Xu, P. Szabo, J. Halekas, H.-W. Shen, J. Deca, W. Farrell

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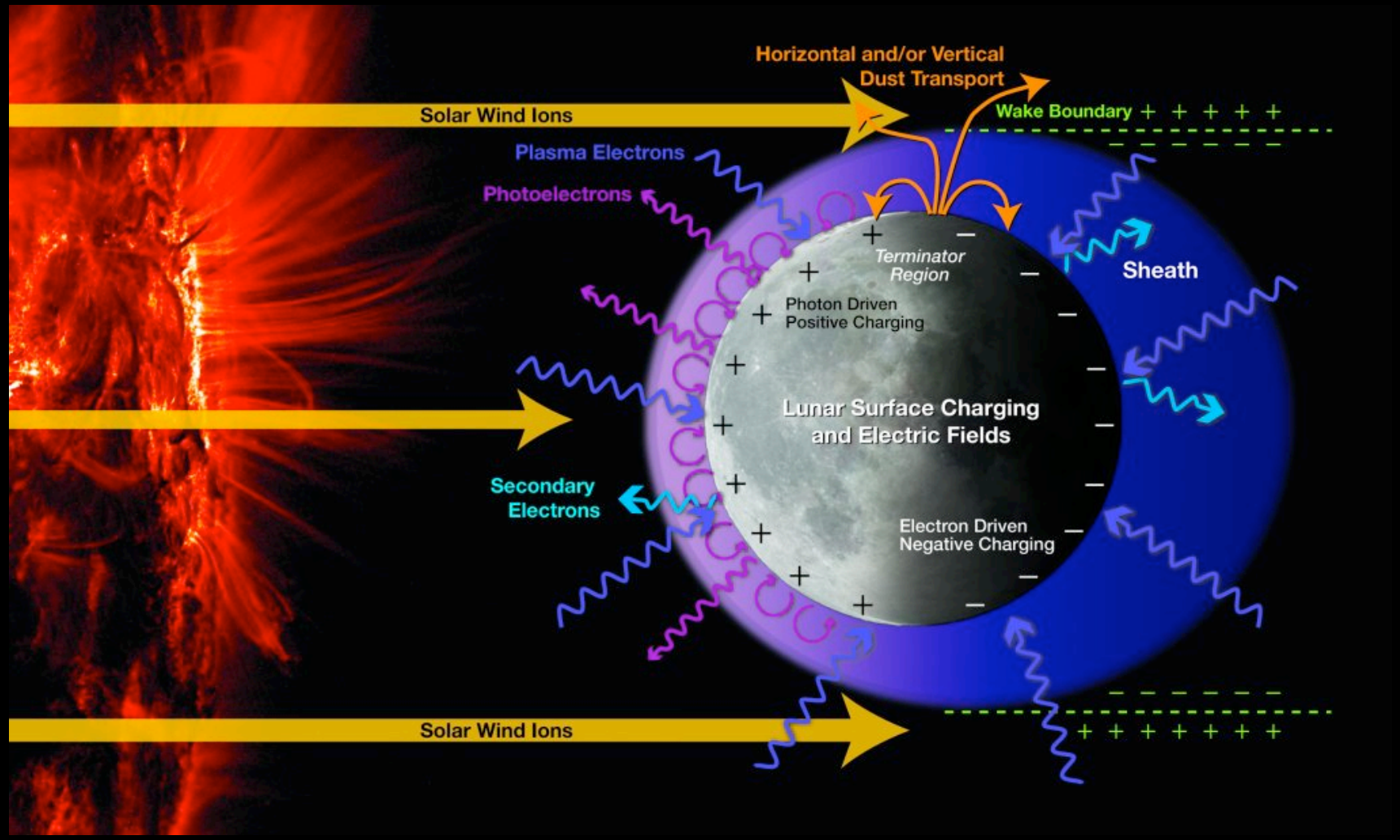
The Lunar Plasma Environment – The Big Picture

The Moon provides an accessible natural laboratory for basic and applied physical research in space sciences



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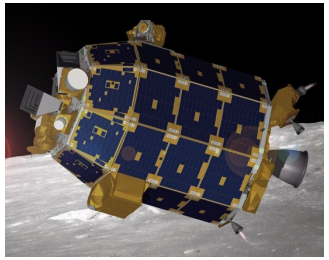
The Lunar Plasma Environment – Past, Current & Future Exploration

Lunar Prospector

Chang'E 1

LADEE



Chang'E 4

PRISM / Lunar Vertex

Gateway / HERMES

Artemis III?

SIMPLEx 3?

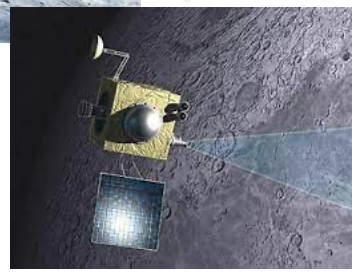
1990

2000

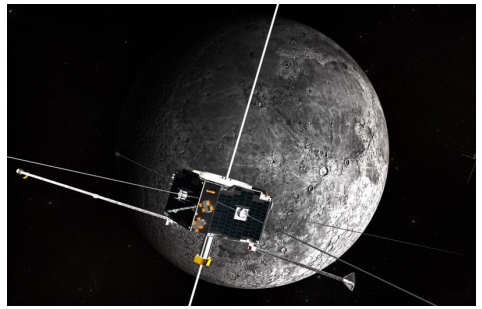
2010

2020

Kaguya



Chandrayaan 1



ARTEMIS

KPLO

Recent Science Results:

I. Surface interactions with plasmas

II. The complex plasma environment within lunar magnetic anomalies

III. The unique environment of the terrestrial magnetotail

IV. The mystery of the lunar "ionosphere"…

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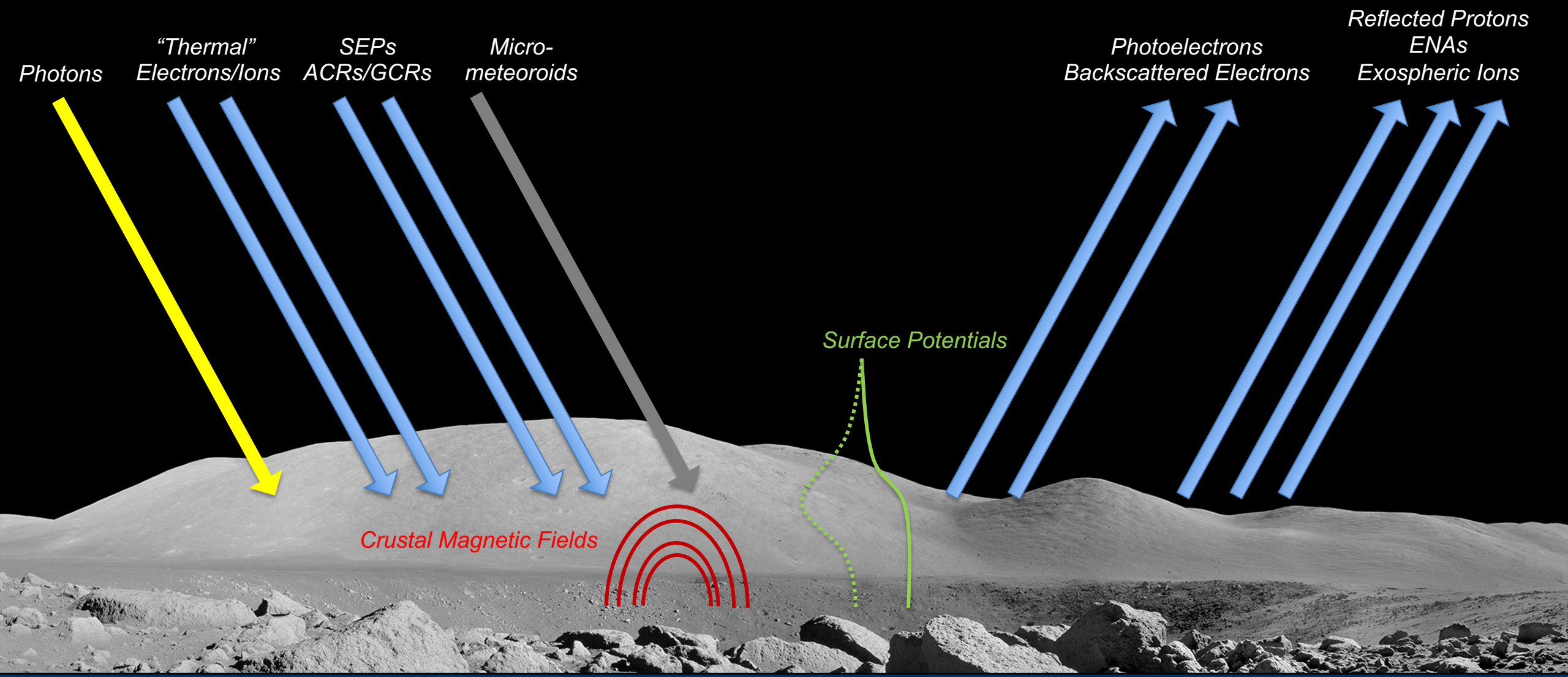
Recent Science Results:

I. Surface interactions with plasmas

Lunar Surface-Plasma Interactions: The Big Picture



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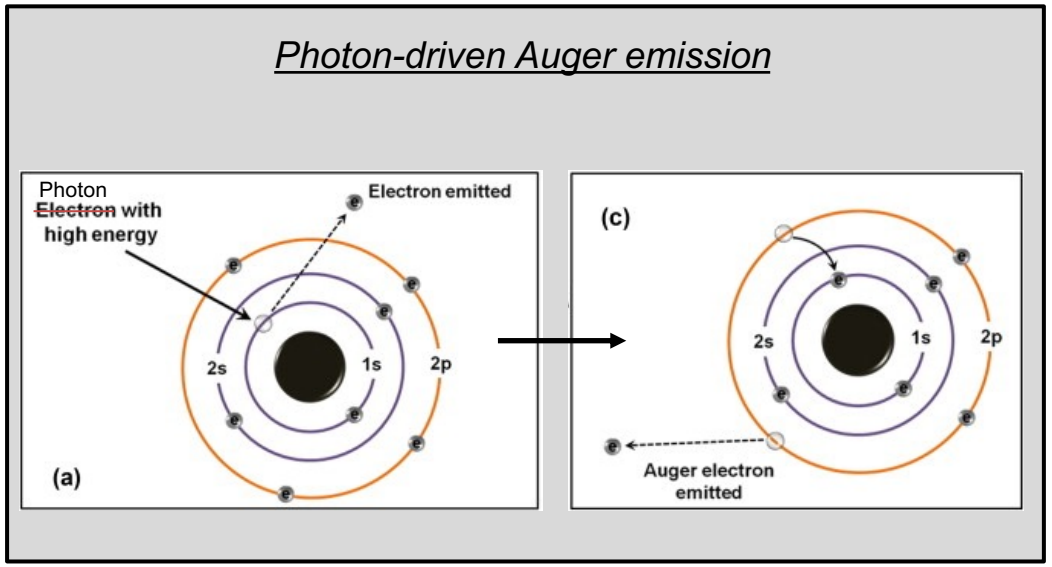
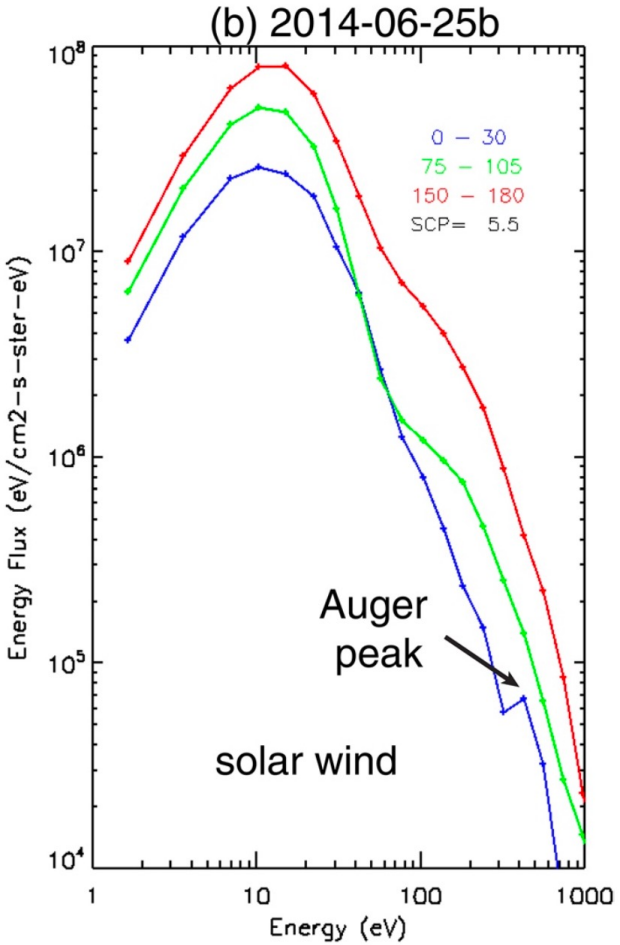
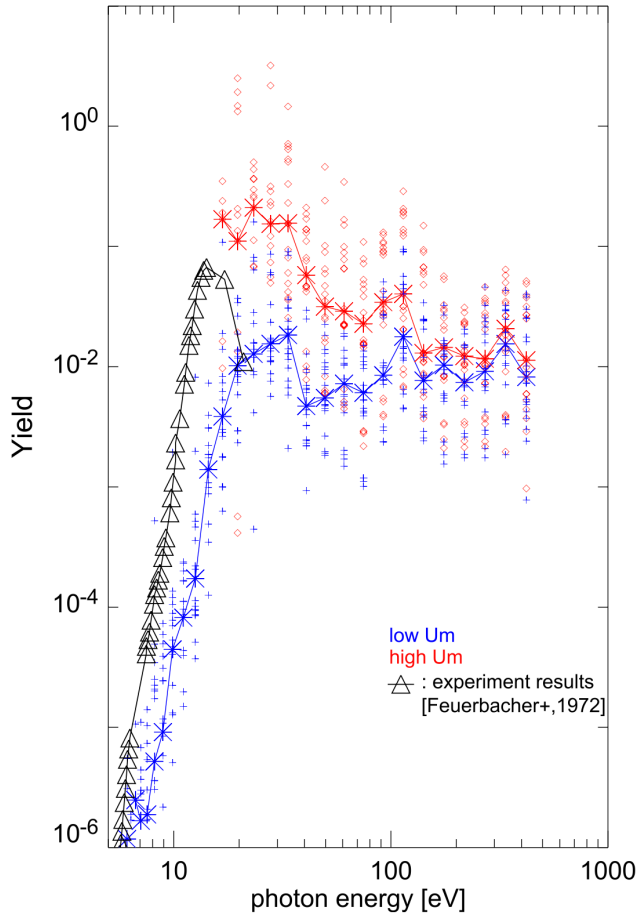
Lunar Surface-Plasma Interactions: Photoemission Yields

In-situ photoelectron measurements can be used to determine the photoemission yield of lunar soil



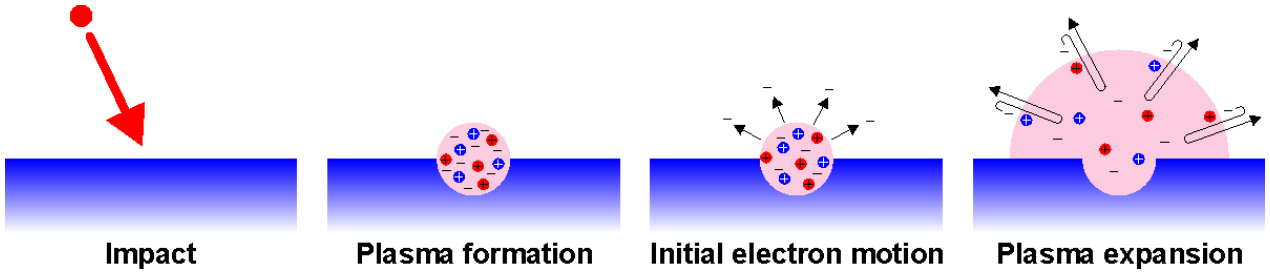




Xu et al., JGR, 2021

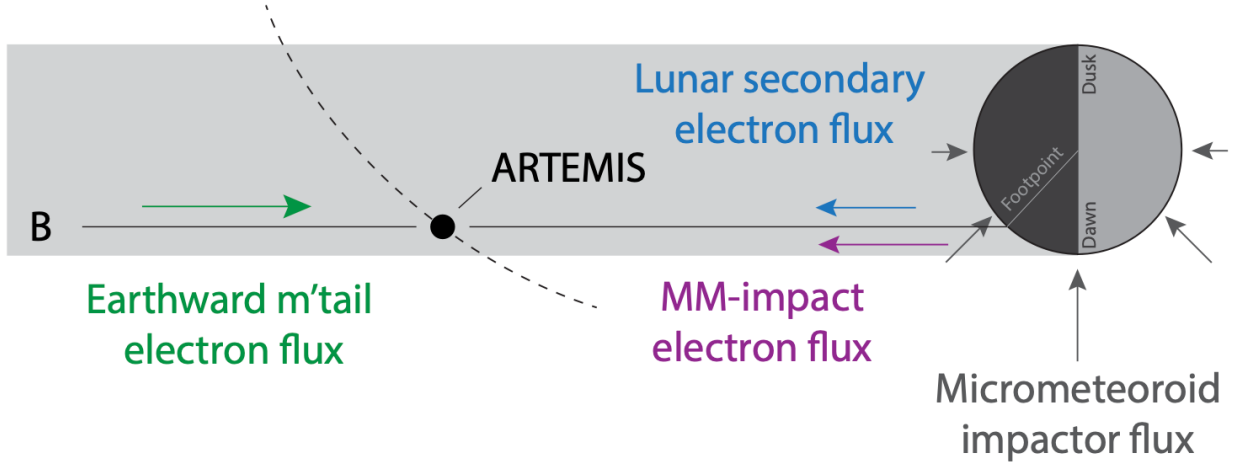
Lunar Surface-Plasma Interactions: Micrometeoroid Impact Charging

In low-density environments, micrometeoroid impacts can dominate surface charging of airless bodies



Credit: Stanford

(a) Connection to the dawn hemisphere



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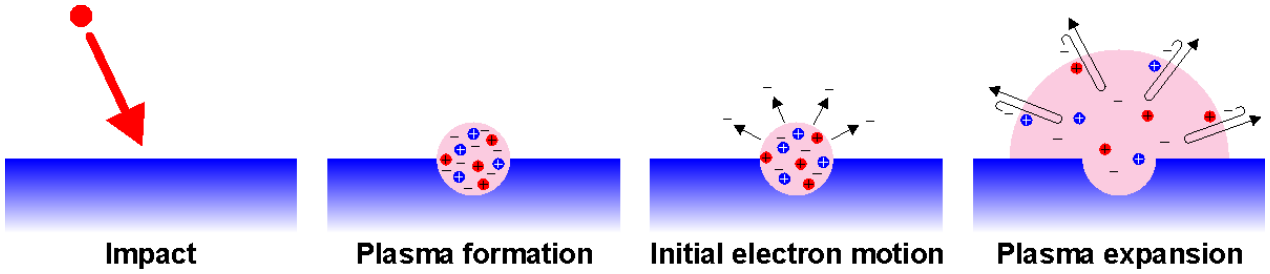
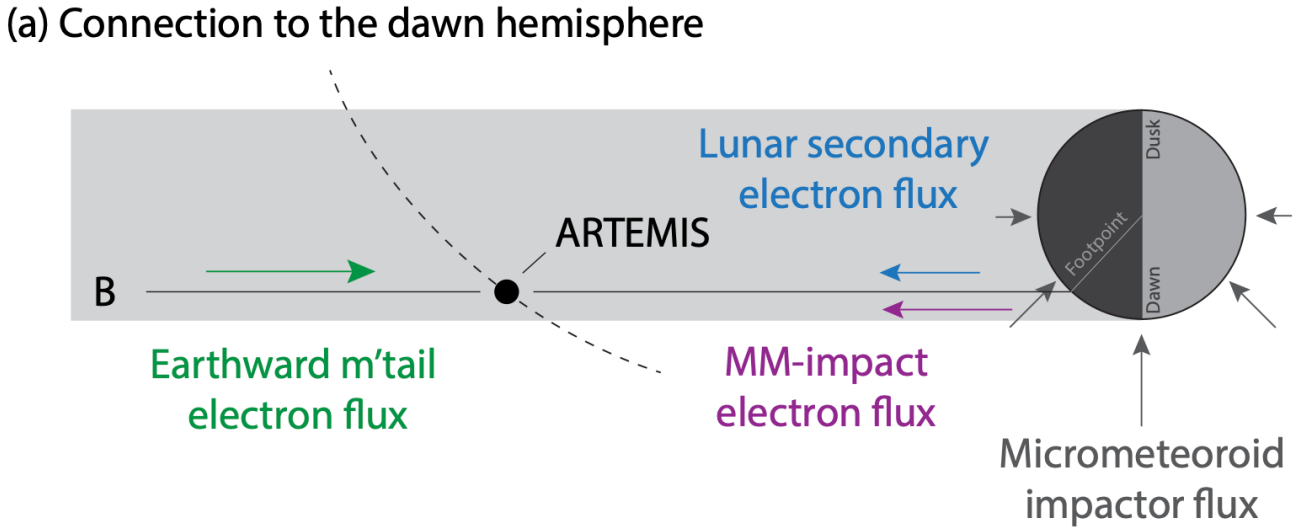
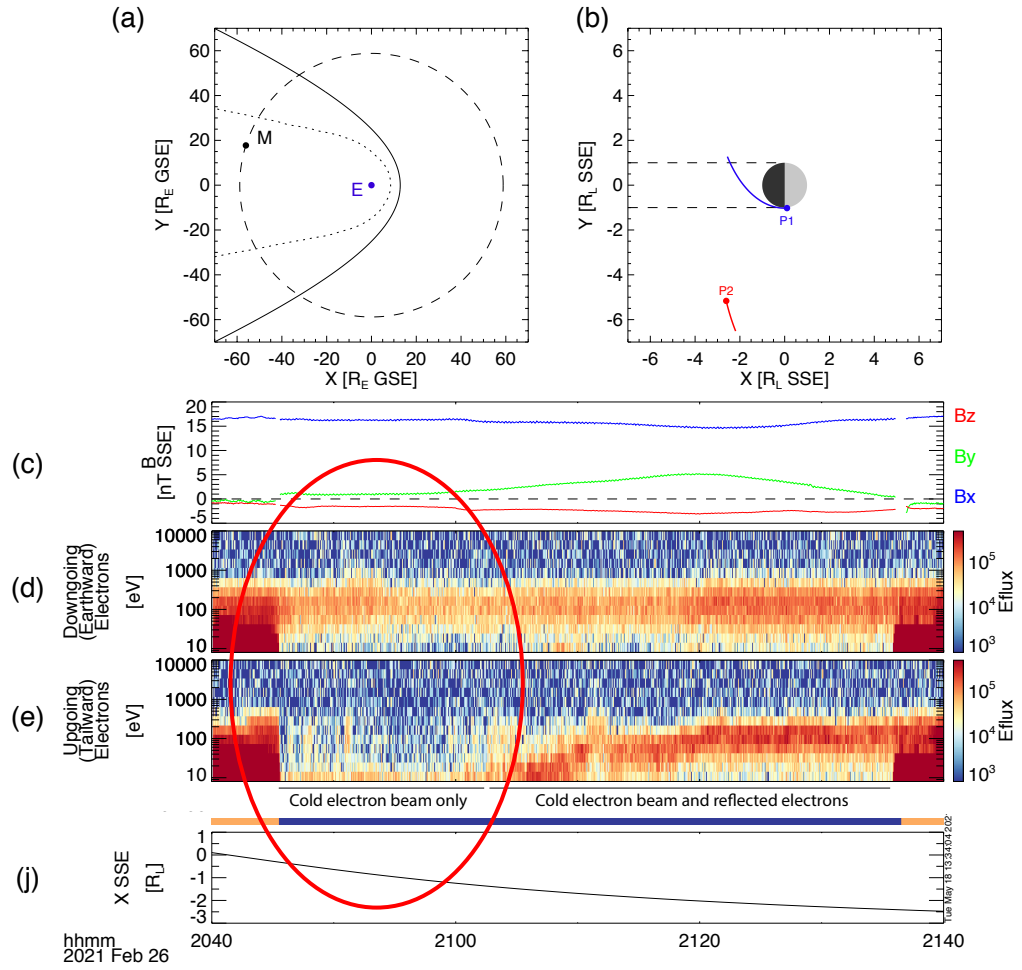


Credit: Stanford

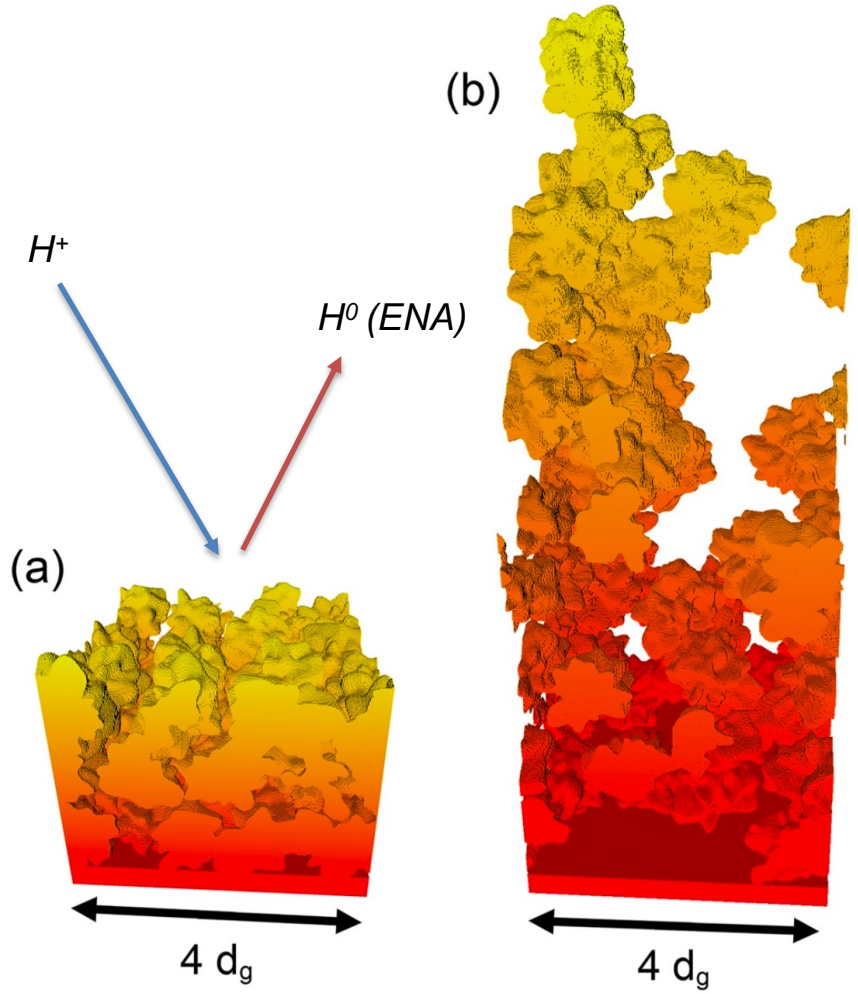


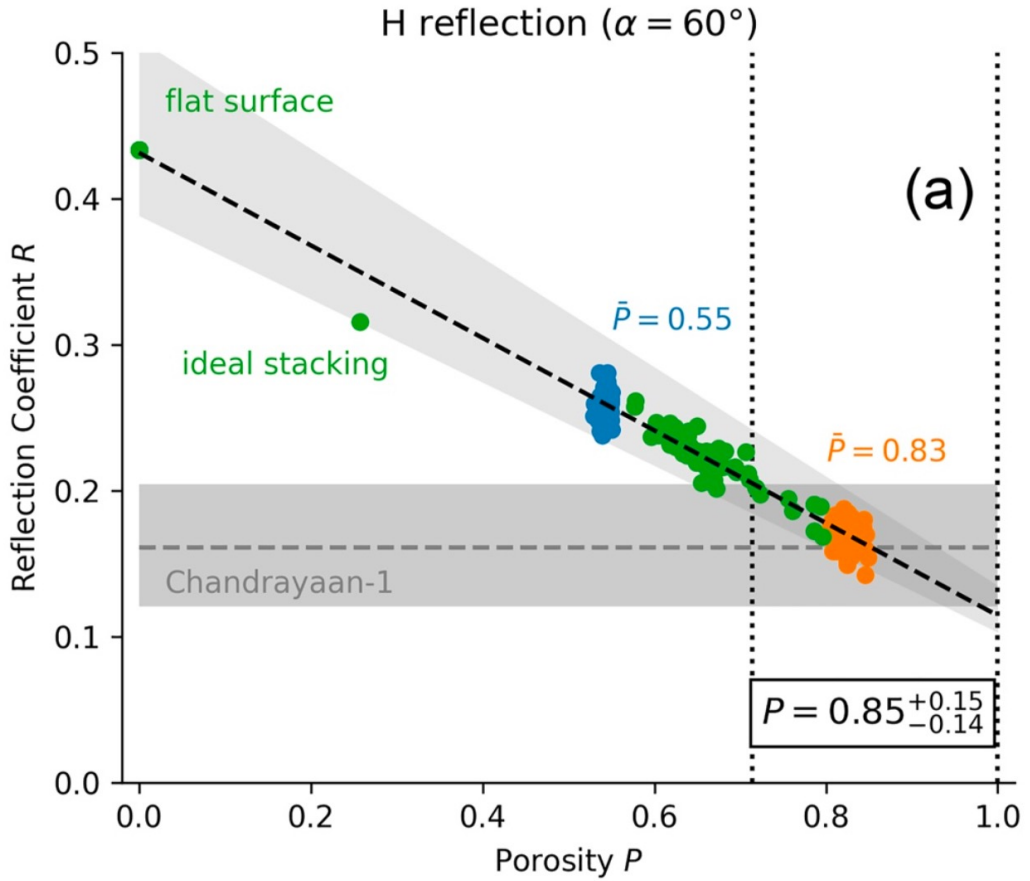


Poppe et al., GRL, 2021

Lunar Surface-Plasma Interactions: Energetic Neutral Atoms

ENA measurements & modeling can be used to constrain *micro-physical* properties of the lunar soil

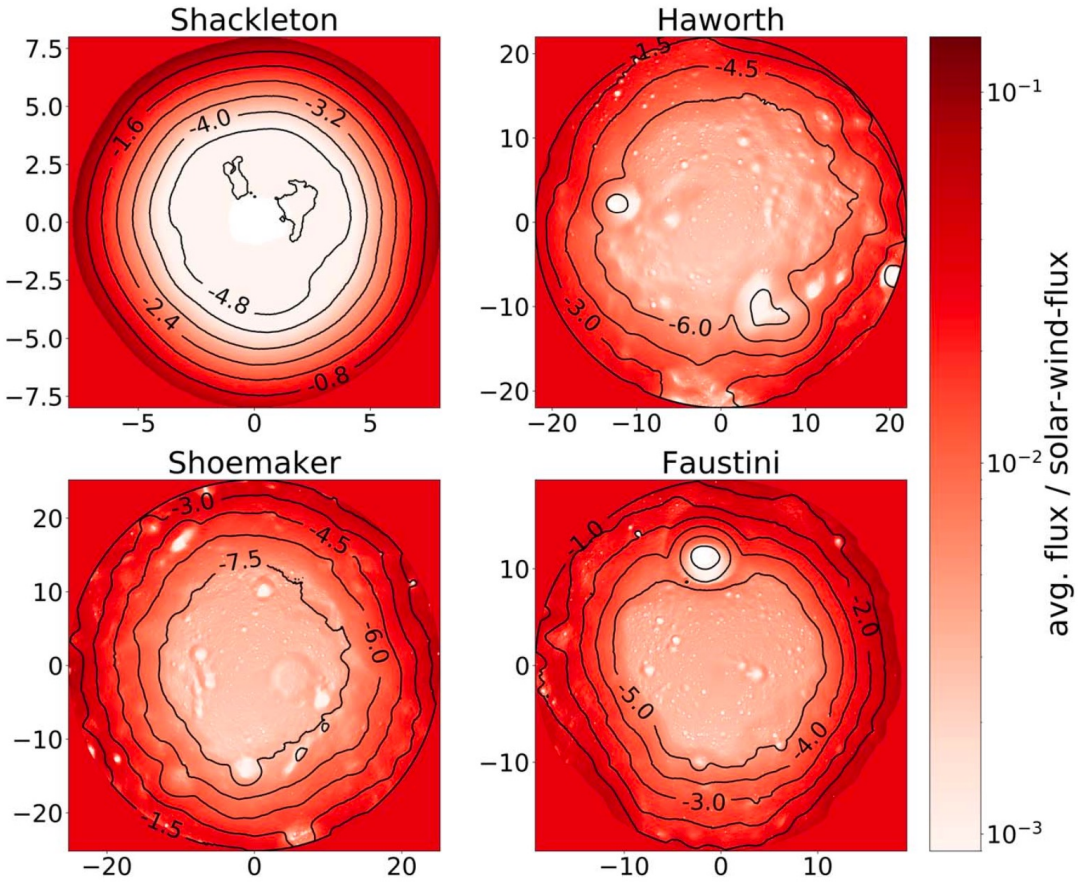




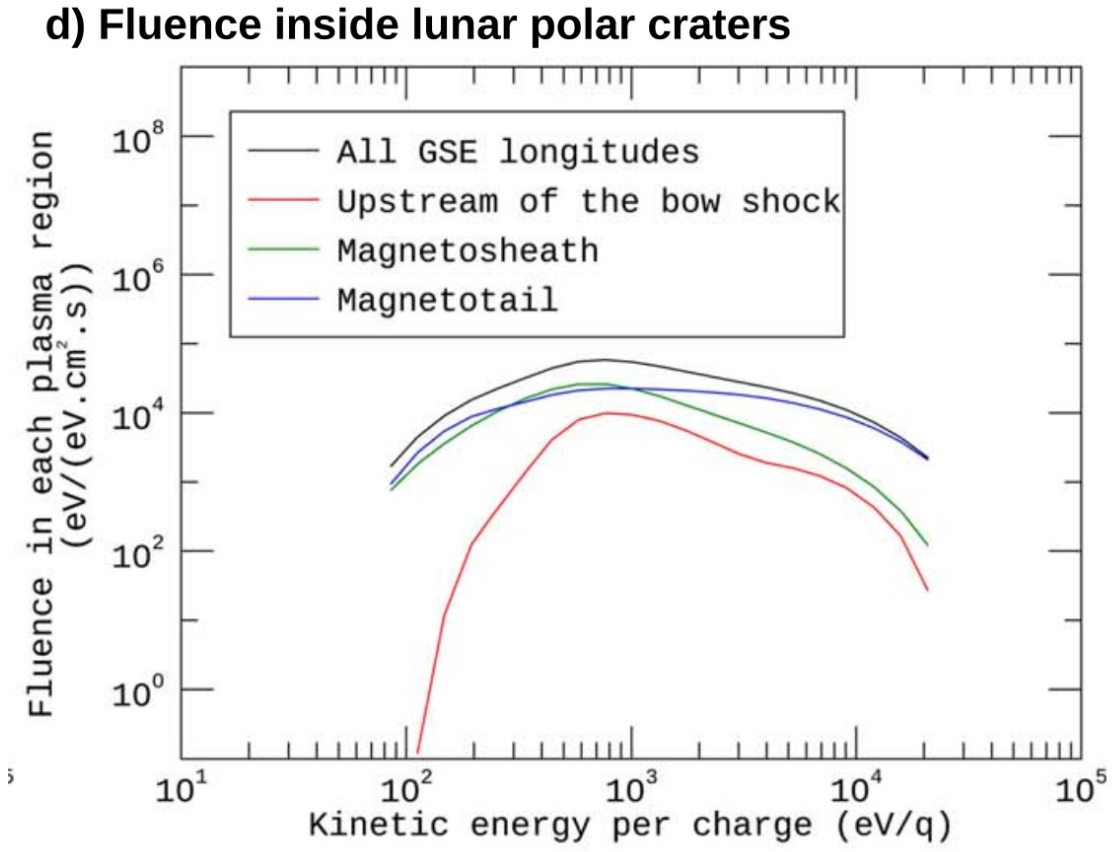
Szabo et al., GRL, 2022

Lunar Surface-Plasma Interactions: Polar Regions

Lunar polar regions are not entirely protected from charged-particle irradiation



Rhodes and Farrell, PSJ, 2020



Nénon and Poppe, PSJ, 2021

Lunar Surface-Plasma Interactions: Open Questions

- How does lunar surface charging respond to extreme solar events?
- How does charged-particle irradiation modify the soil within lunar polar regions?
- Are negative ions produced as a result of micrometeoroid-impact plasmas on the lunar surface?
- What can we infer about surface charging at other airless bodies from our observations at the Moon?

Recent Science Results:

II. The complex plasma environment within lunar magnetic anomalies

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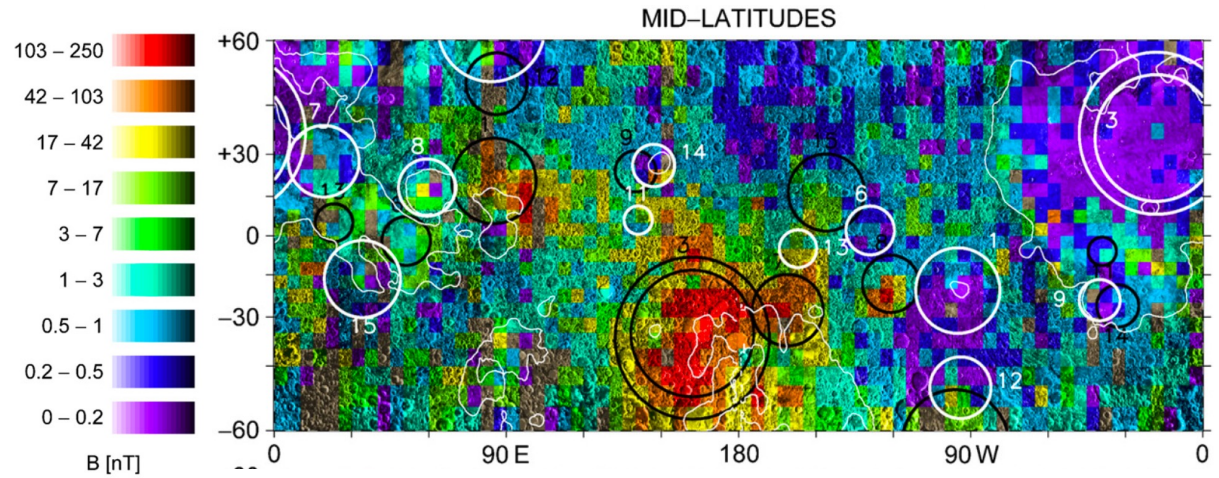
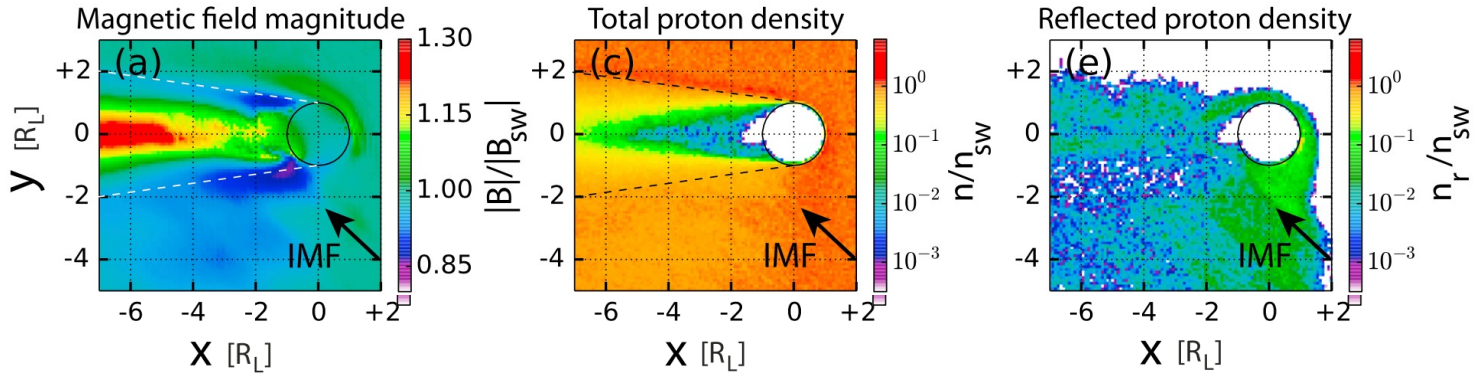
Lunar Magnetic Anomalies: The Big Picture

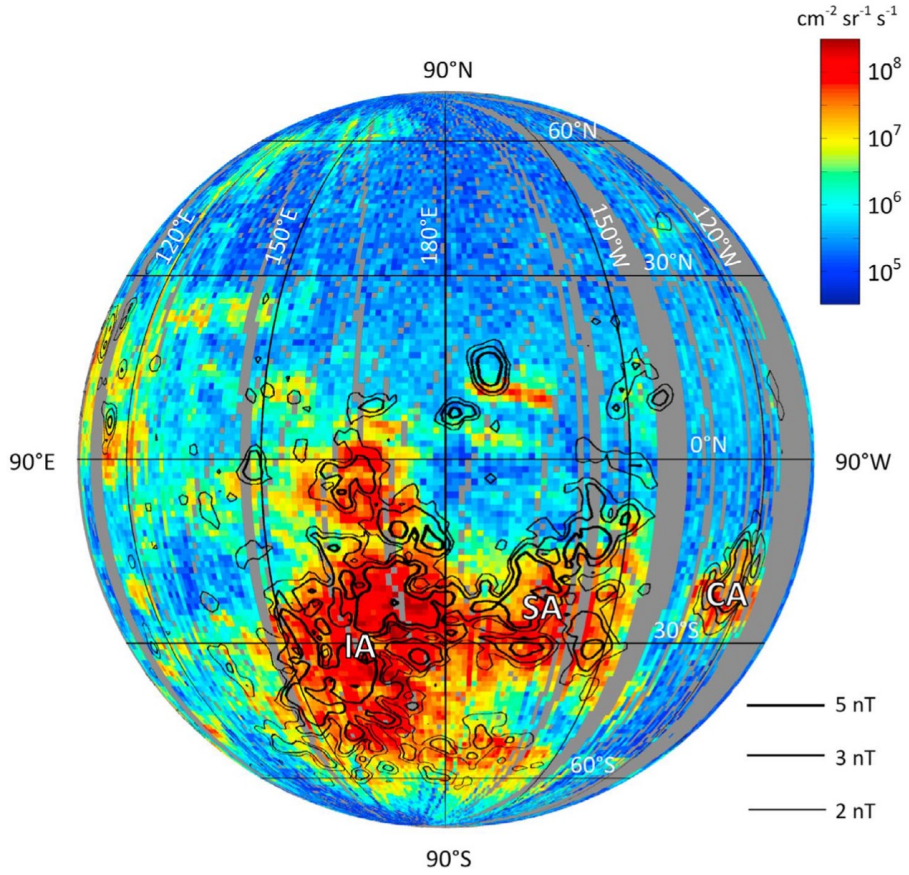
Widespread crustal magnetic fields have strong influence over the Moon's plasma interaction



Mitchell et al., Icarus, 2008



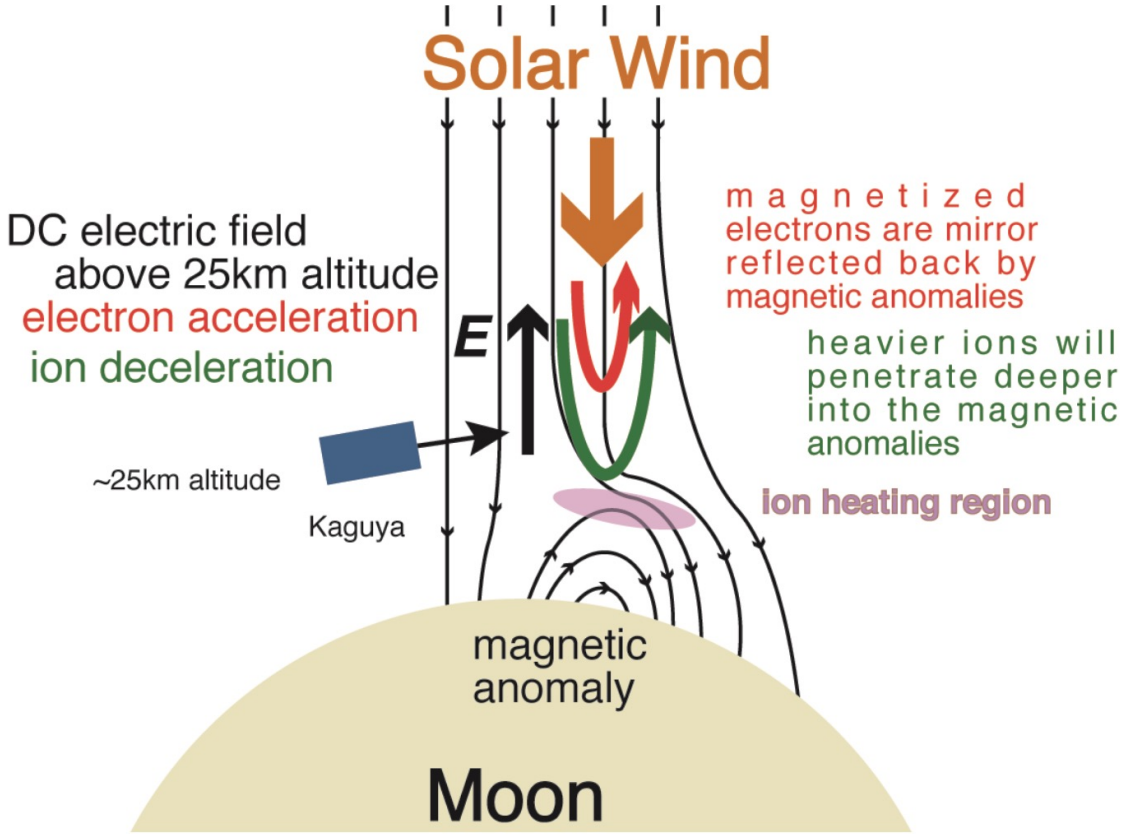
Fatemi et al., JGR, 2014

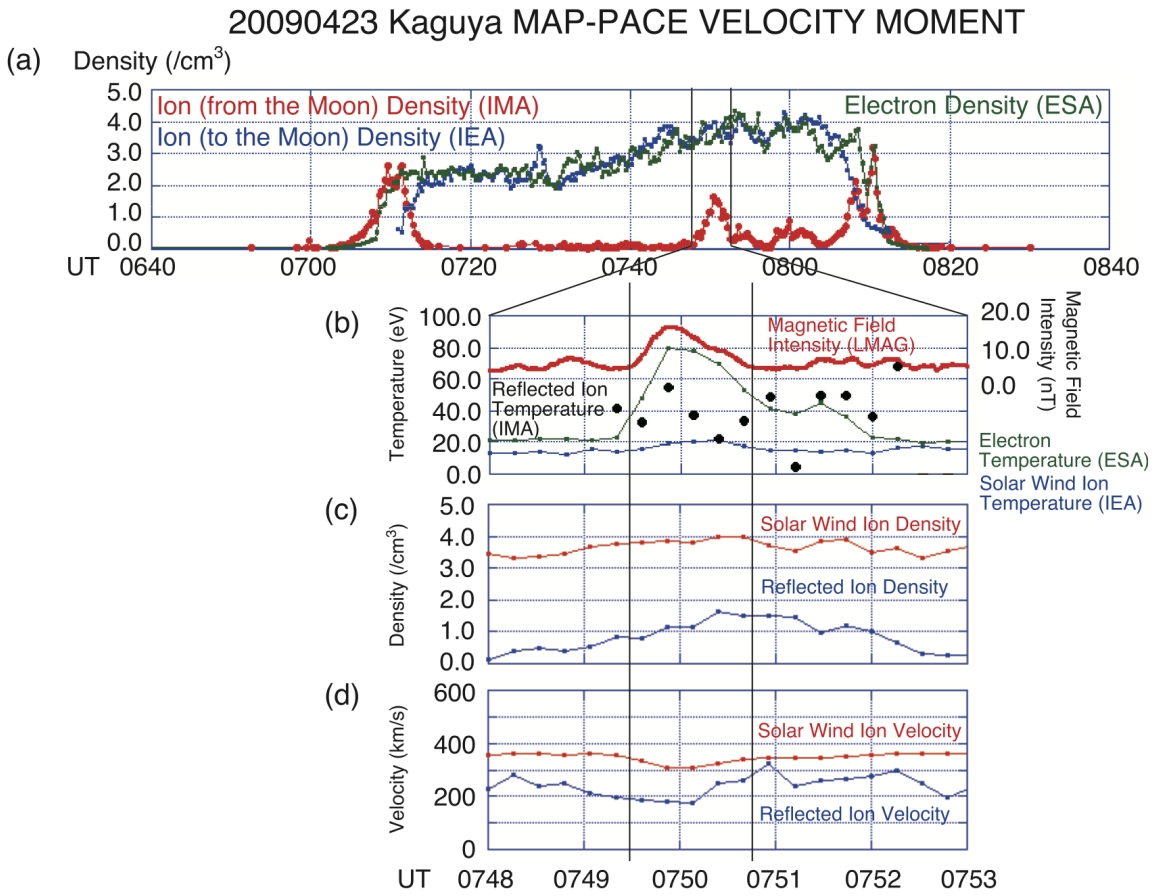


Lue et al., GRL, 2011

Lunar Magnetic Anomalies: Electrodynamic Interactions

Solar wind interactions with magnetic anomalies are rich in kinetic-scale physics

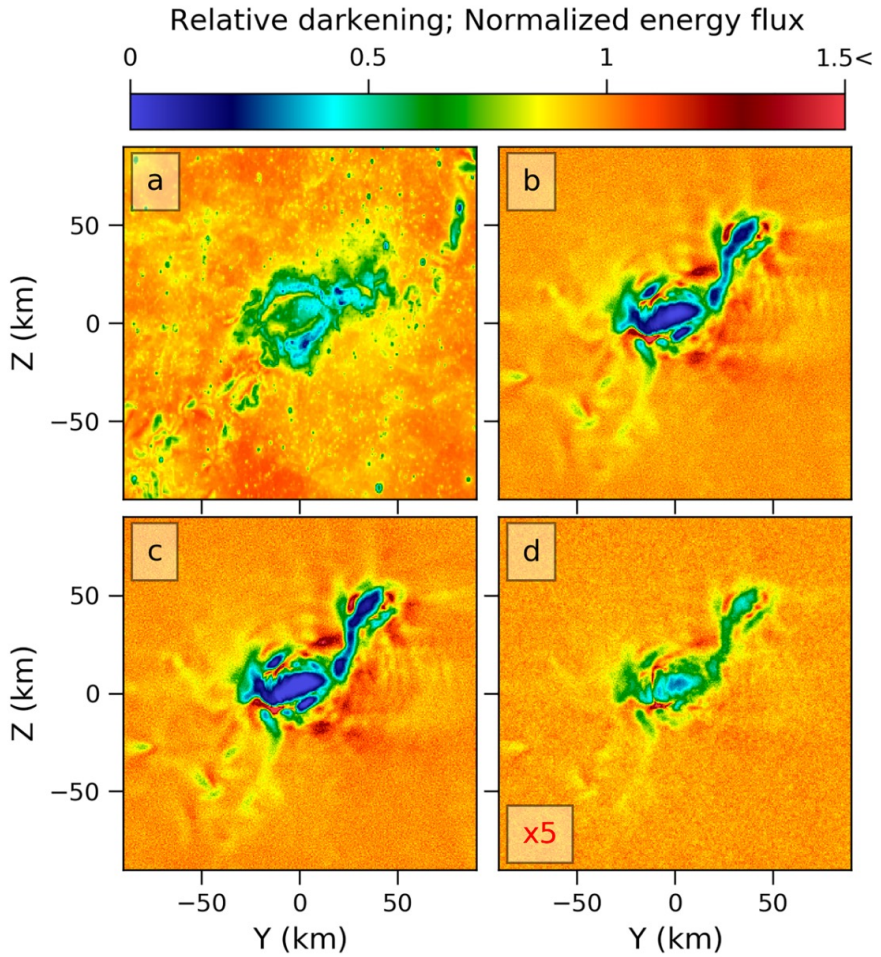




Saito et al., EPS, 2012

Lunar Magnetic Anomalies: Reiner Gamma, the Canonical Anomaly

Kinetic (PIC) simulations can connect surface-weathering patterns to ion precipitation within anomalies



Deca et al., JGR Planets, 2020

Lunar Magnetic Anomalies: Open Questions

- How do crustal anomalies govern weathering rates at the underlying surface regions?
- What is the surface-charging environment within crustal magnetic anomalies?
- Are all lunar magnetic anomalies in the kinetic regime, or do some approach fluid scales?
- Do ‘mini-magnetospheres’ really form, or are crustal anomalies simply too small in scale?

Recent Science Results:

III. The unique environment of the terrestrial magnetotail

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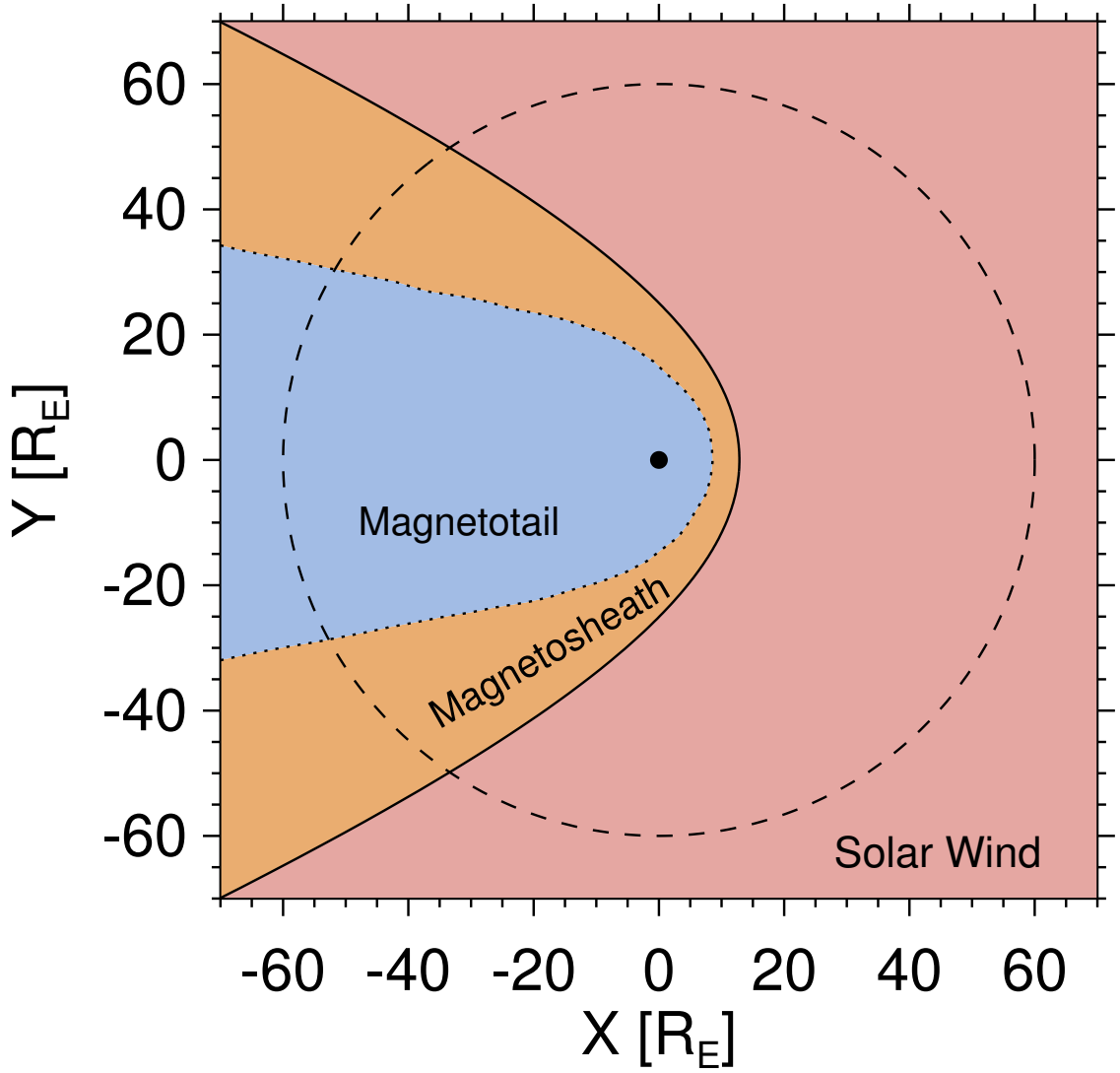
The Moon in the Magnetotail: The Big Picture



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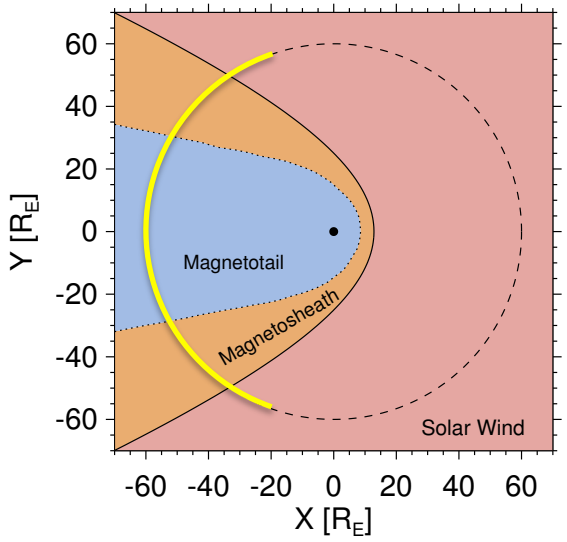
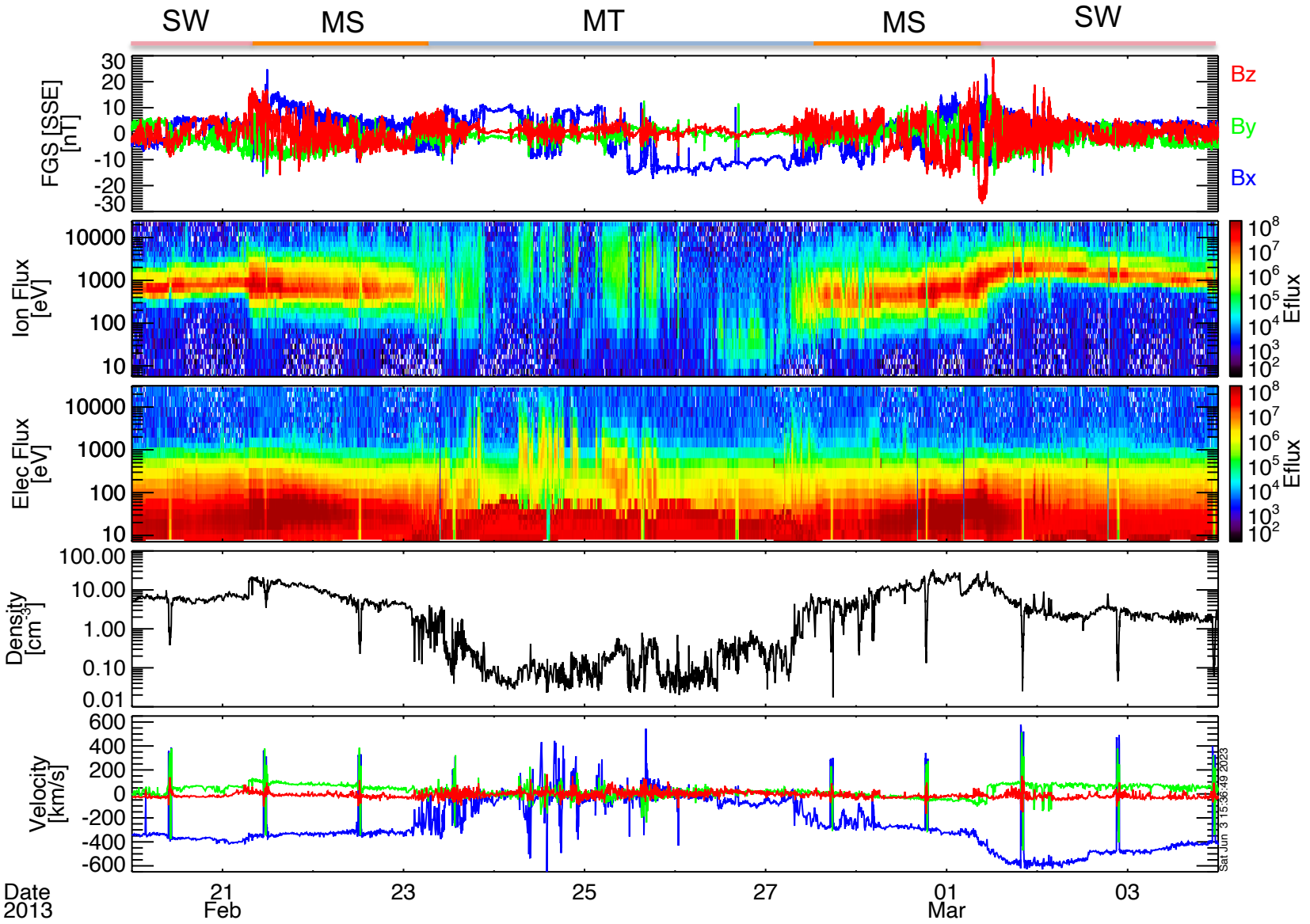
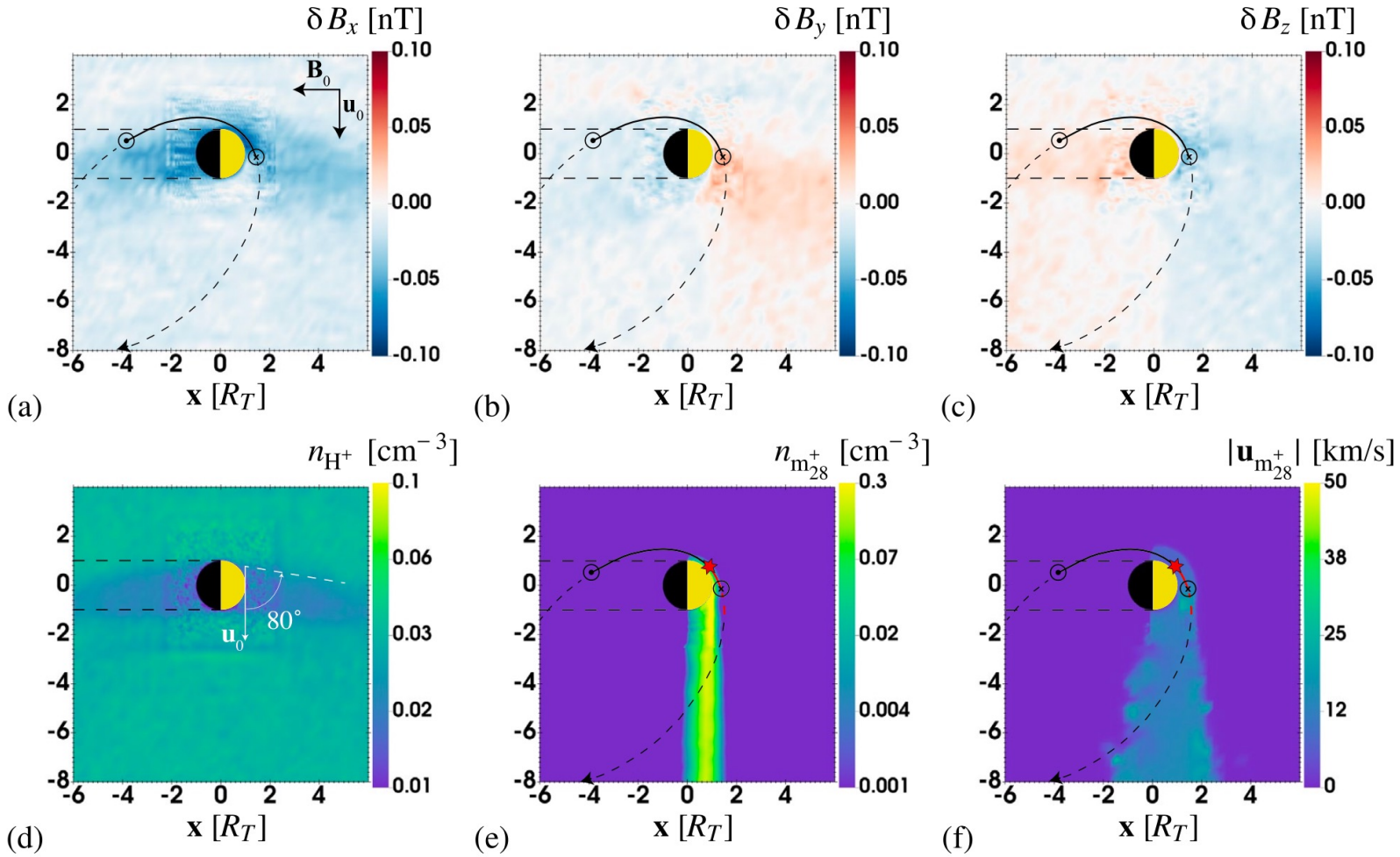




The Moon in the Magnetotail: Interactions with Terrestrial Plasma

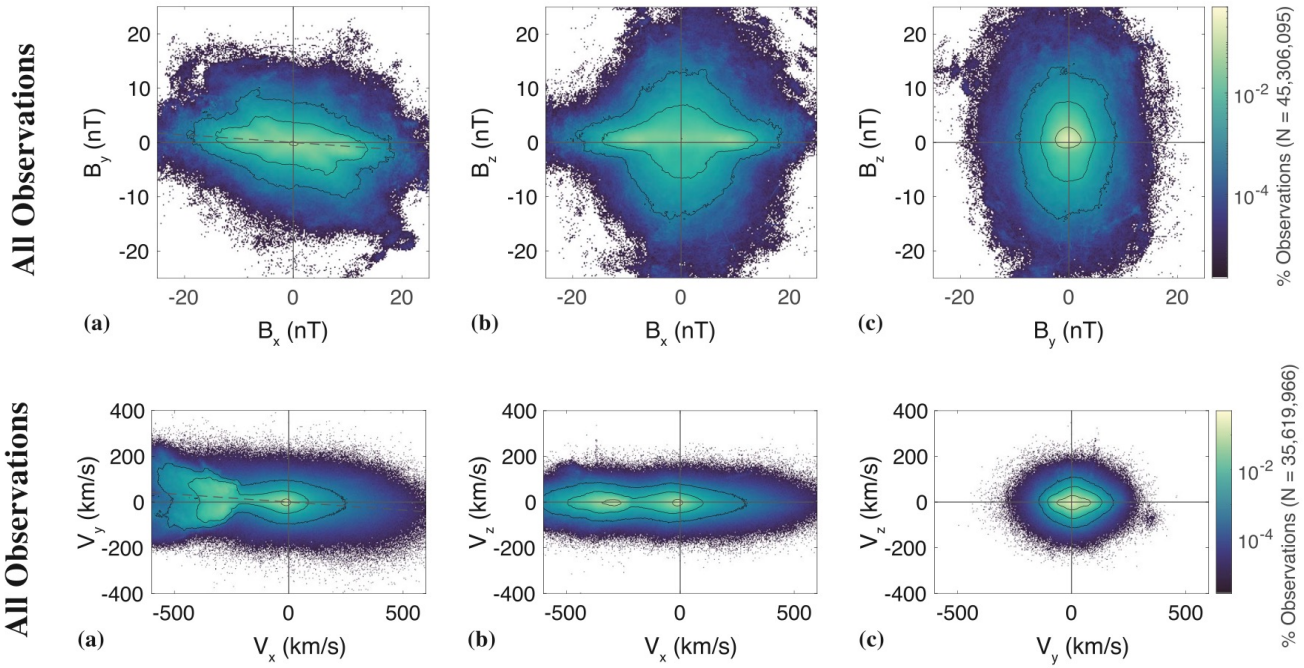
Lunar-plasma interactions in the magnetotail are distinctly different from those in the solar wind

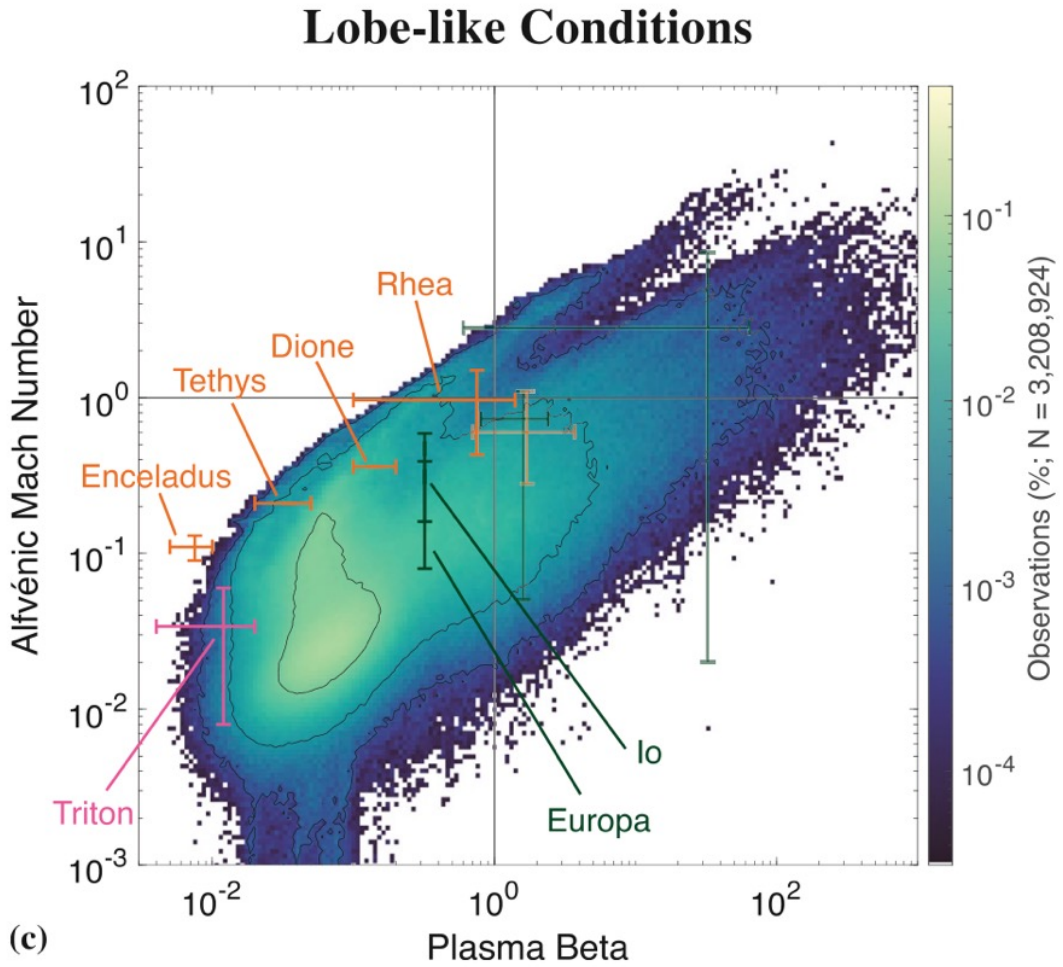


Liuzzo et al., GRL, 2021

The Moon in the Magnetotail: A Statistical View

Terrestrial magnetotail plasma conditions share similarities with outer planet moon-magnetosphere interactions

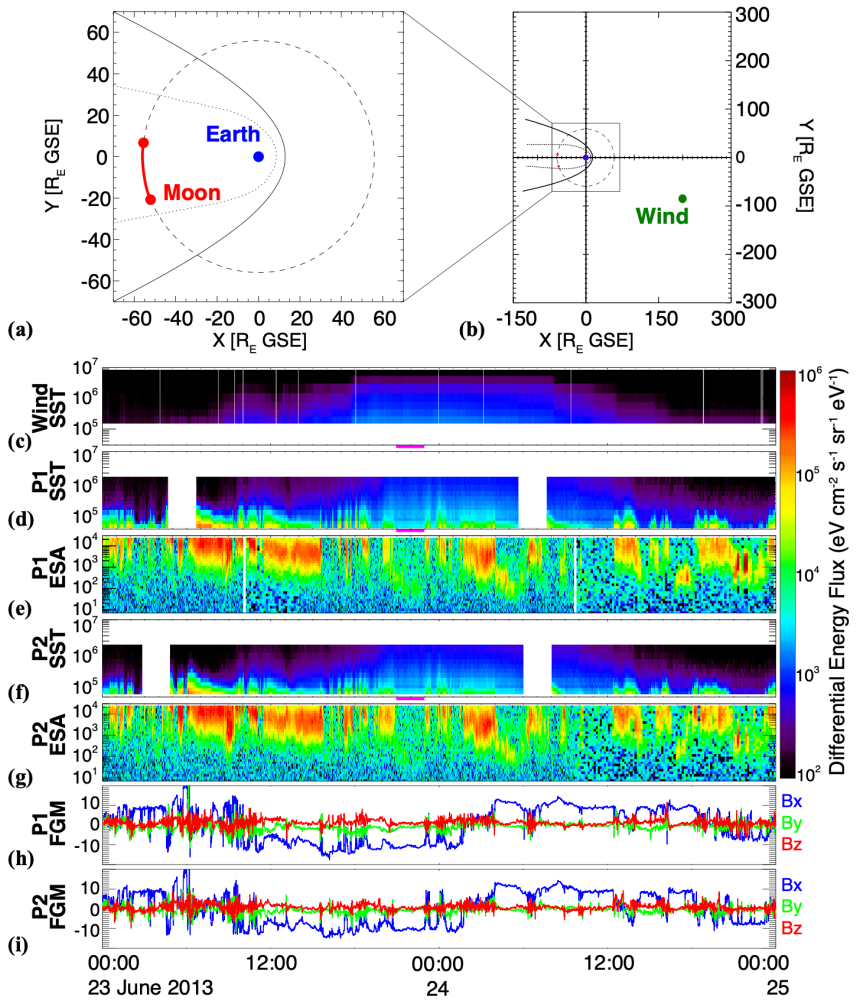


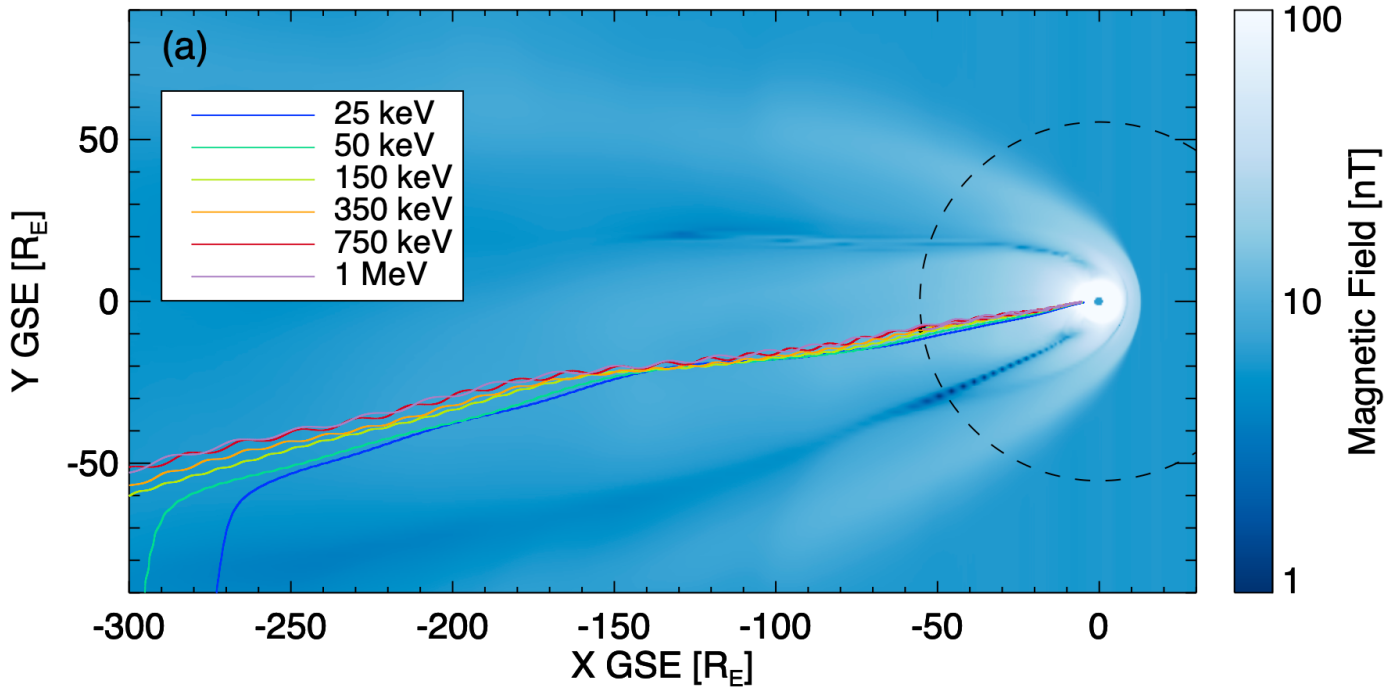


Liuzzo et al., JGR, 2022

The Moon in the Magnetotail: A Porous Boundary for Energetic Particles?

ARTEMIS observes solar energetic particles while crossing the magnetotail





Liuzzo et al., GRL, in review

The Moon in the Magnetotail: Open Questions

- How do moon-magnetosphere interactions compare between Earth's Moon in the magnetotail and the moons of the outer planets?
- How are lunar exospheric ions transported (and potentially recirculated) through the terrestrial magnetotail?
- Does the terrestrial magnetotail provide any shielding from solar energetic particles? Or even partial shielding?
- How can plasma observations at the Moon help to further understand magnetotail dynamics?

Recent Science Results:

IV. The mystery of the lunar “ionosphere”…

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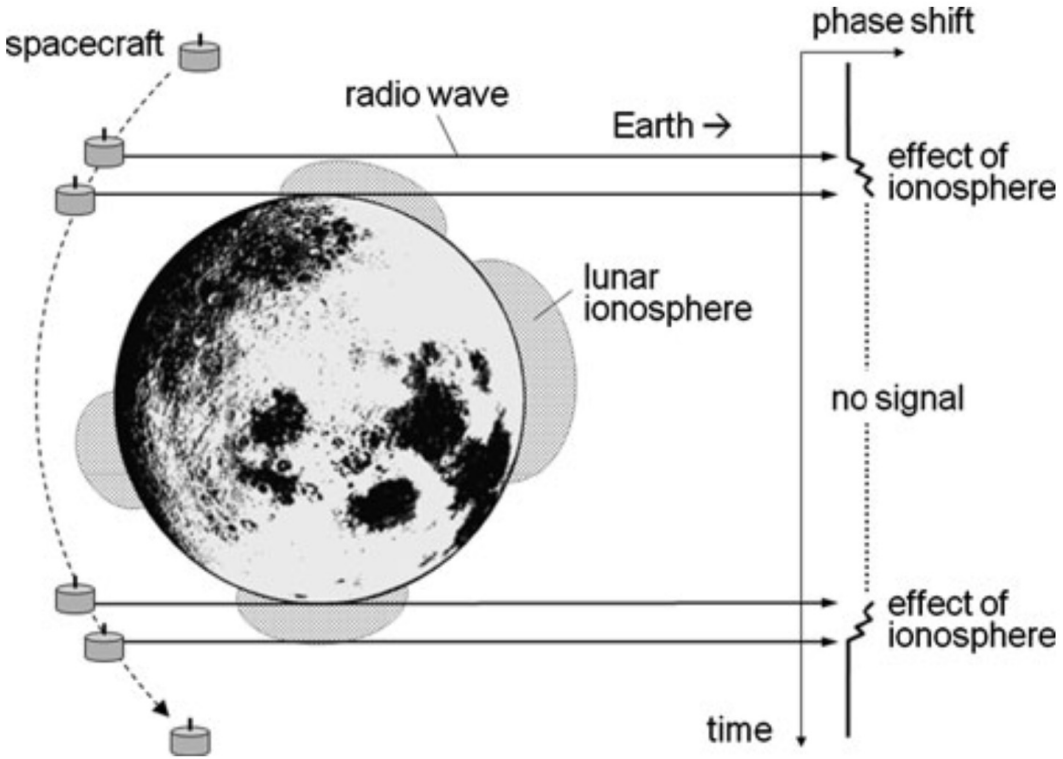
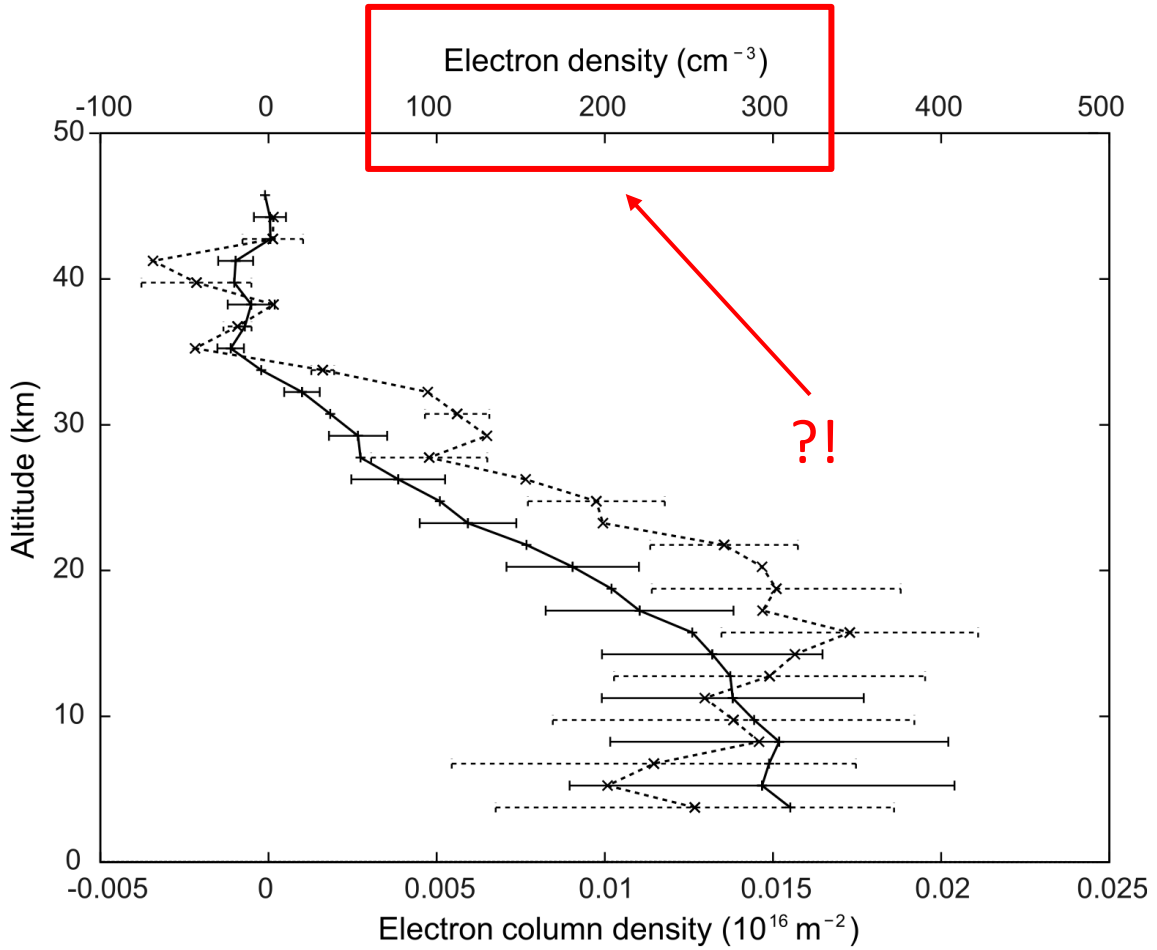
The Lunar "Ionosphere": The Big Picture

Radio-occultation measurements suggest a dense, potentially "patchy" lunar ionosphere



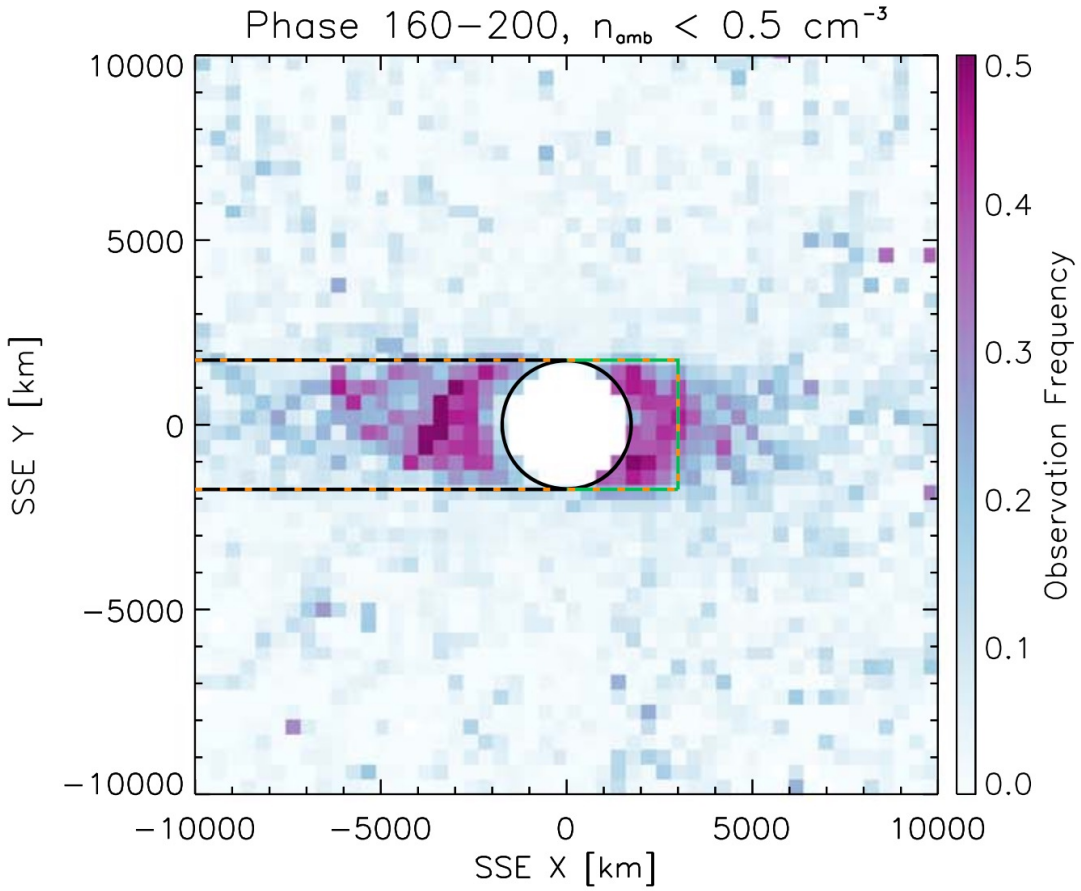
Imamura et al., SSR, 2010

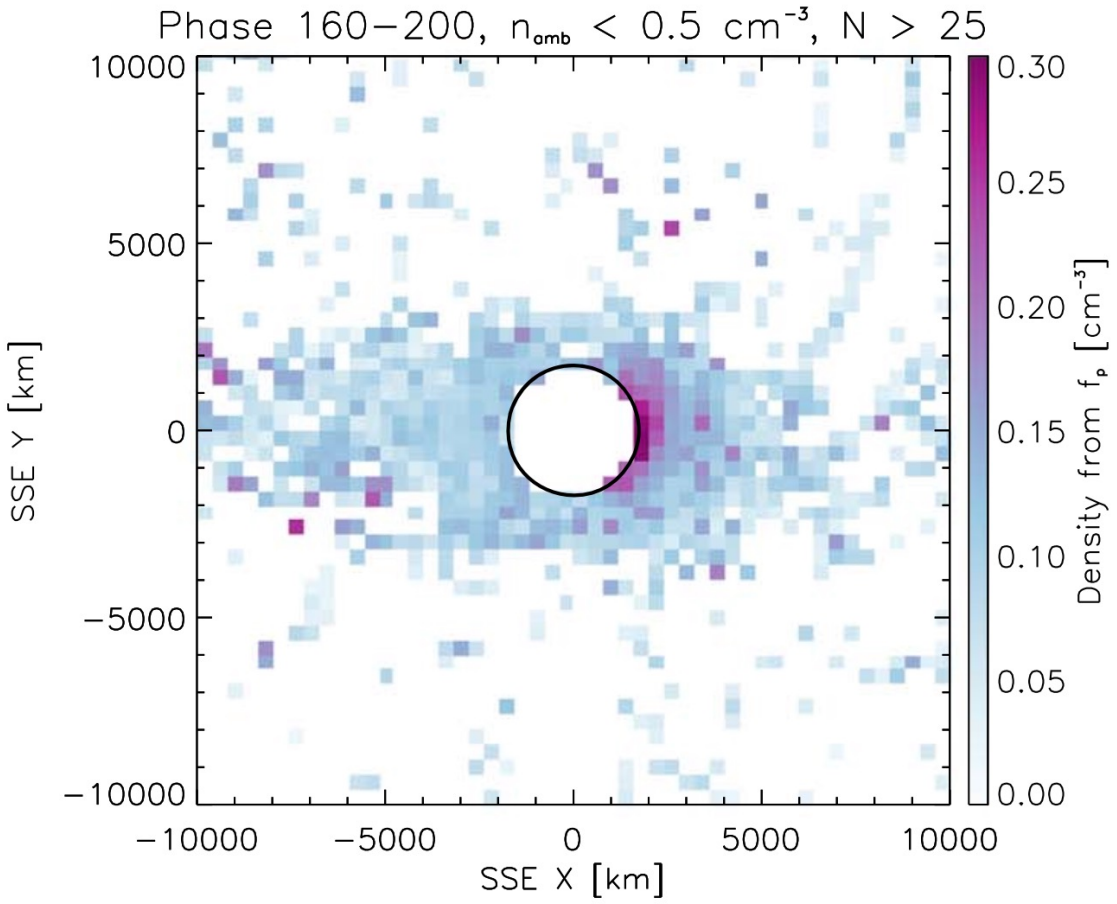


Imamura et al., GRL, 2012

The Lunar "Ionosphere": ARTEMIS Observations in the Magnetotail

In the magnetotail, the near-lunar environment is dominated by plasma of lunar origin

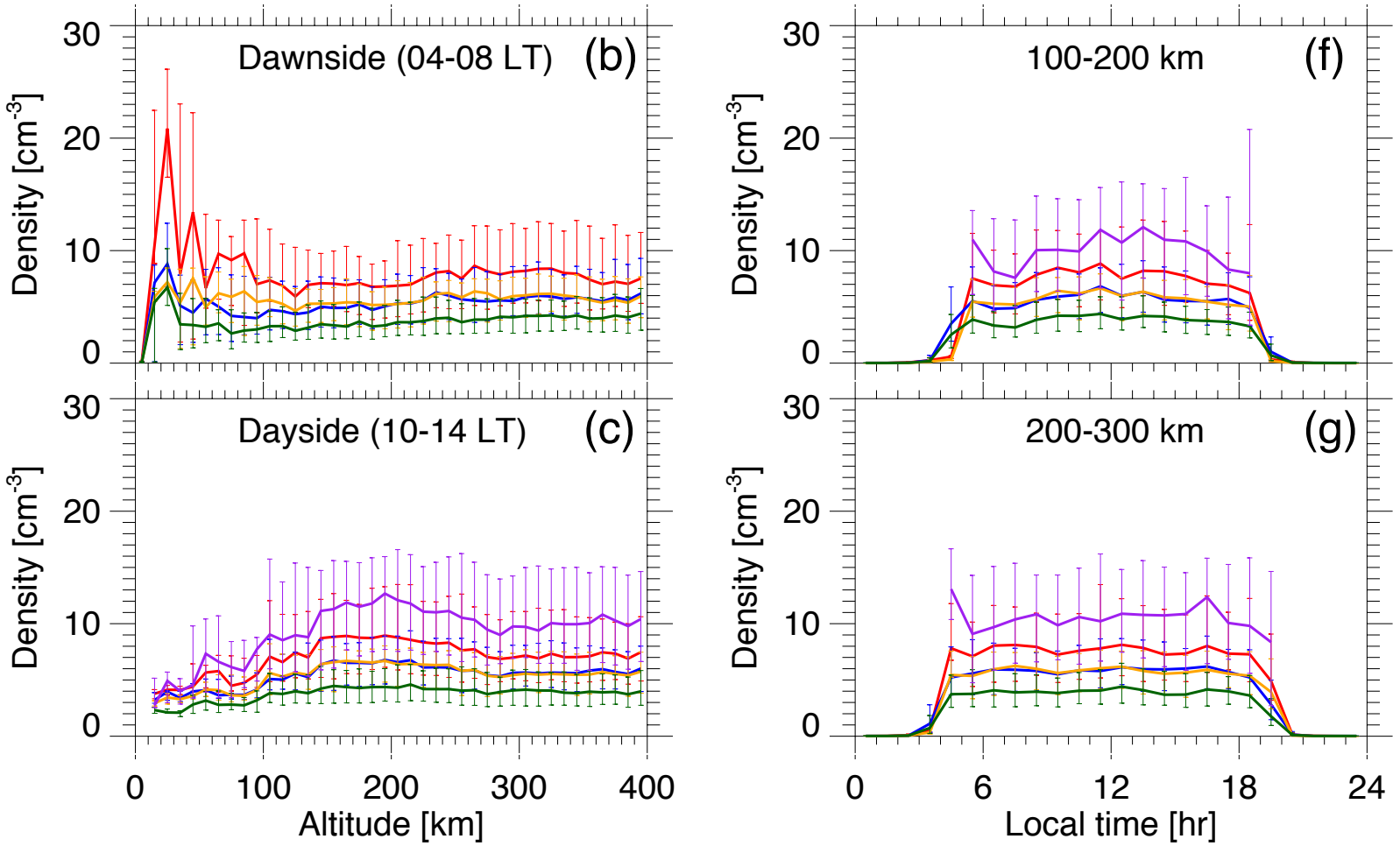




Halekas et al., GRL, 2018

The Lunar "Ionosphere": Upper Limits from ARTEMIS

ARTEMIS provides **no evidence** for a dense (n > 20 cm^{-3}) lunar ionosphere



Shen et al., GRL, in review

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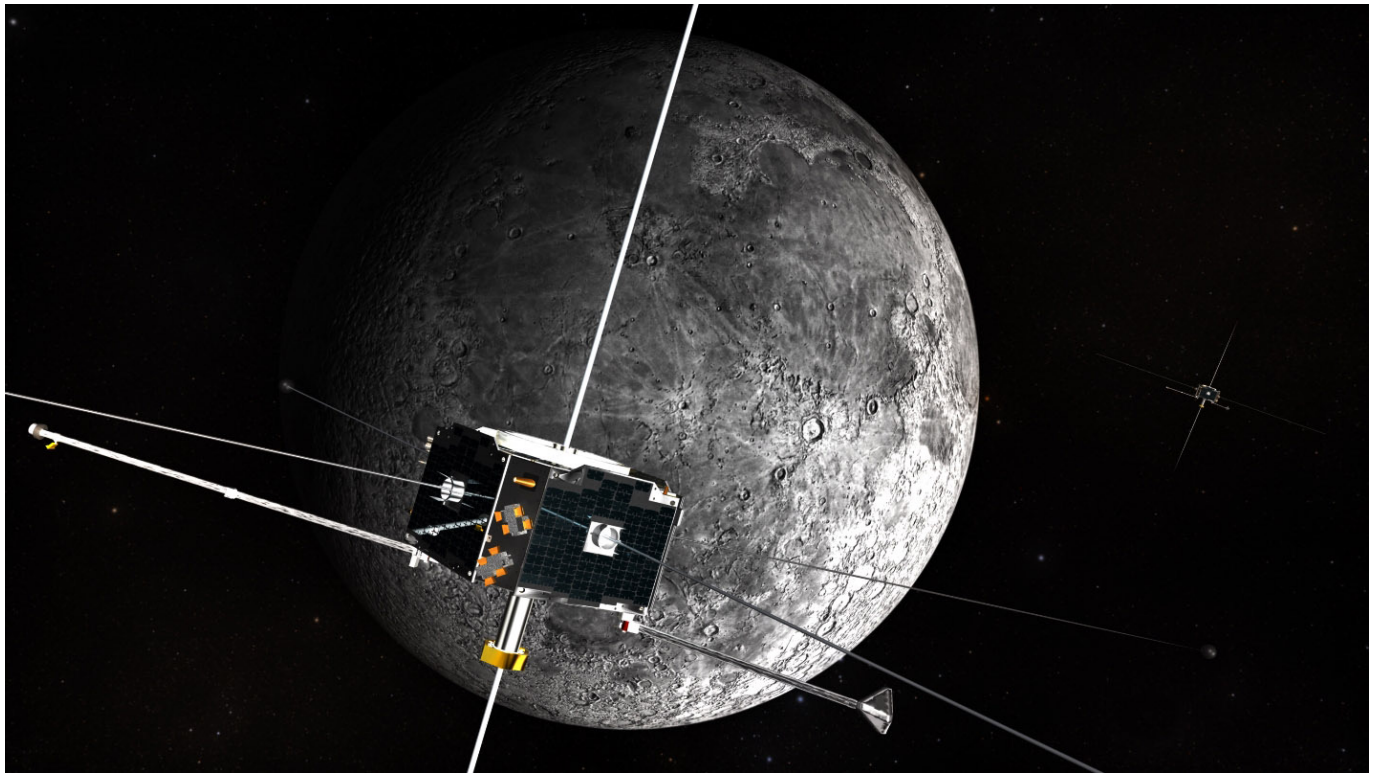
The Lunar Ionosphere: Open Questions

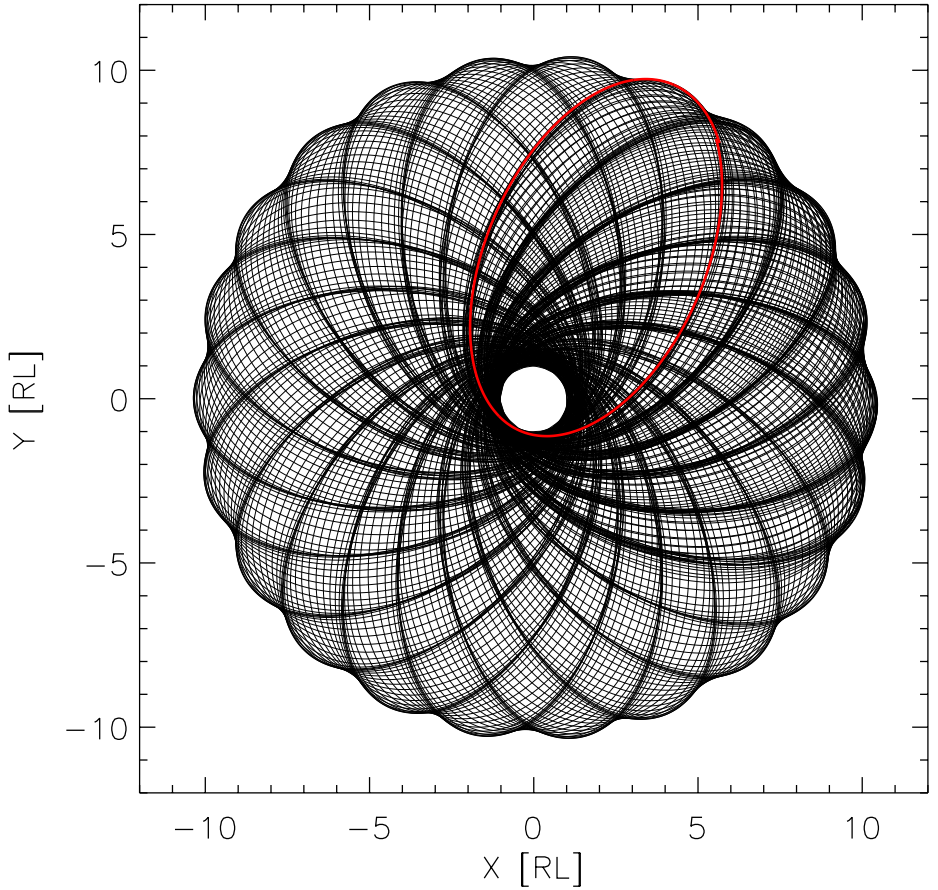
- What is the density and spatial extent of the lunar ionosphere?
- Are there multiple components (i.e., global + patchy) to the lunar ionosphere?
- If there is a patchy lunar ionosphere, what causes it (e.g., impact plasma plumes)?
- If there is a patchy lunar ionosphere, does it disturb the solar wind interaction with the Moon on local/regional scales?

Future Directions

ARTEMIS: 12 Years with Many More to Come

ARTEMIS remains in excellent health and provides critical scientific and operational observations



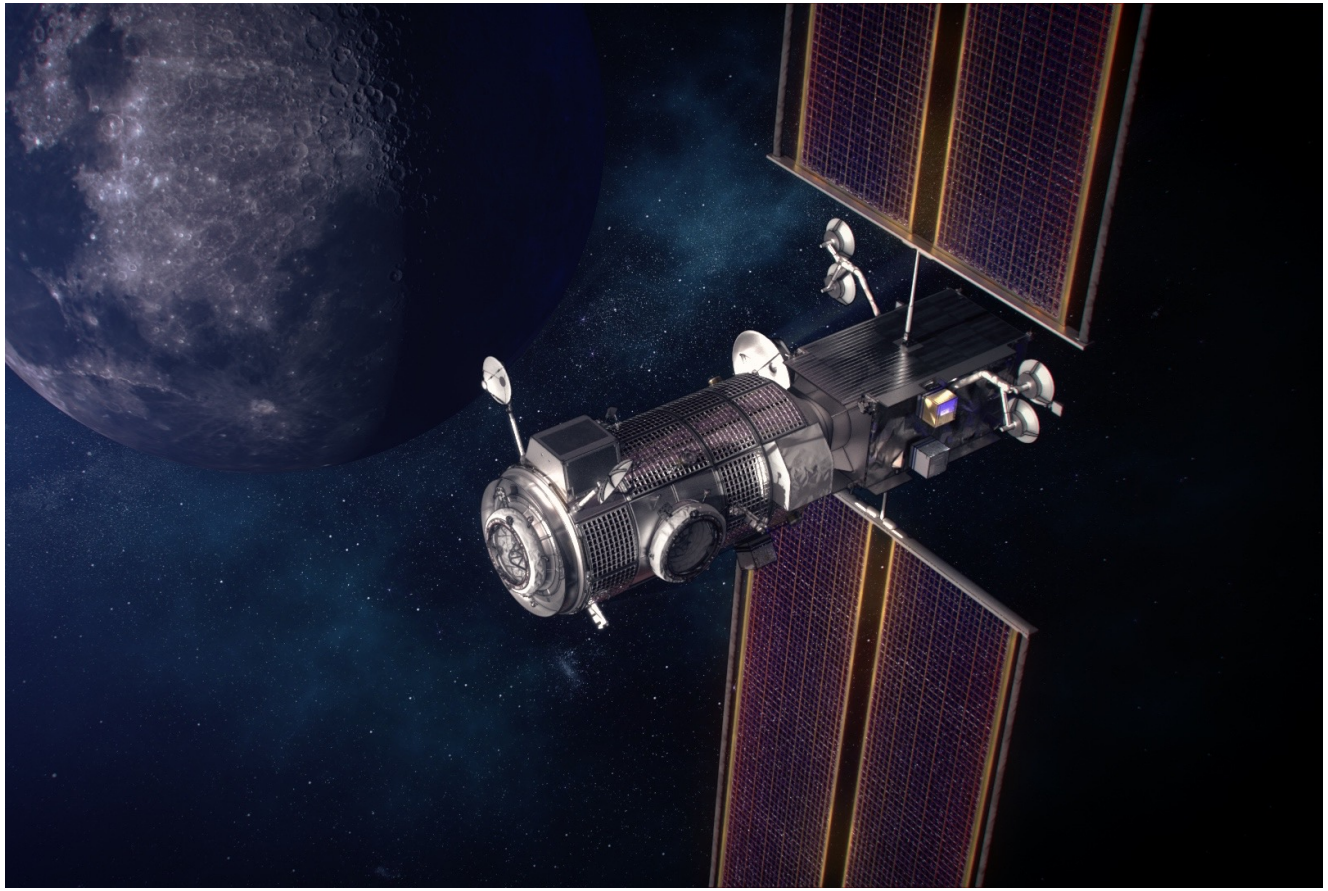


ARTEMIS data are publicly available at https://artemis.ssl.berkeley.edu or via NASA/CDAWeb

Lunar Gateway & HERMES

Plasma/field environmental monitoring at the Moon with the addition of ion mass resolution

Lunar Gateway



SPAN-ion Instrument

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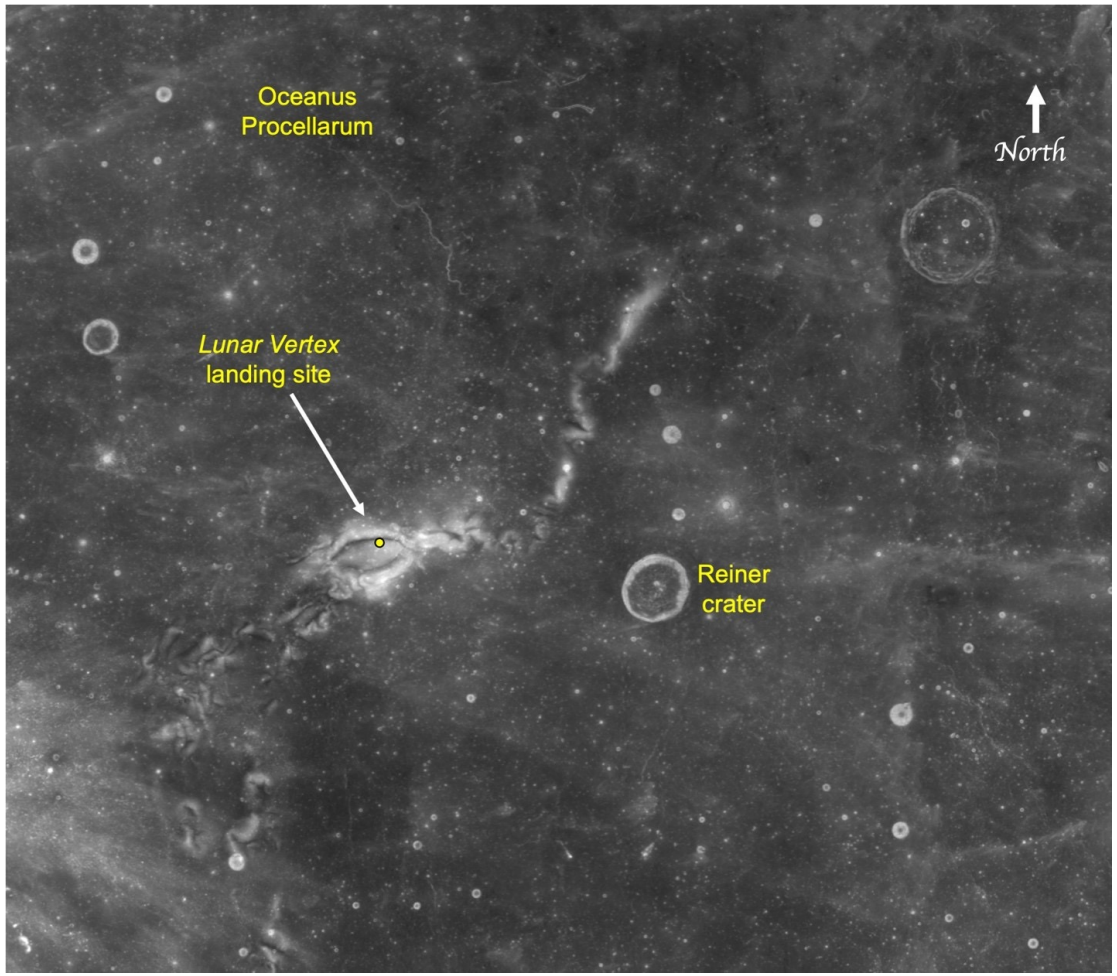
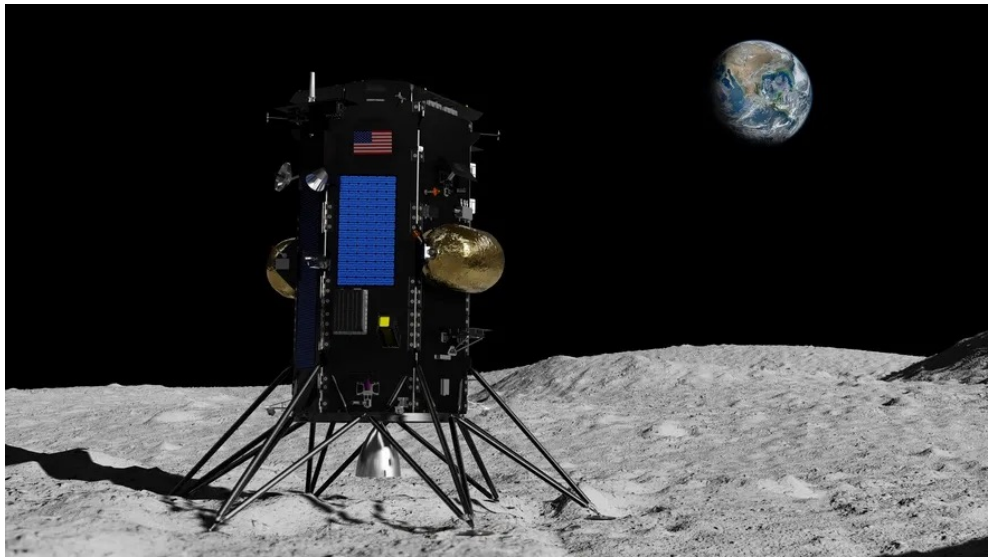
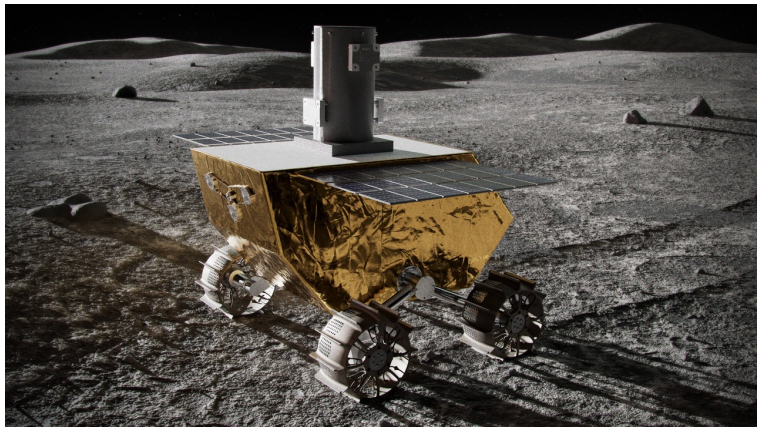
Lunar Vertex: Mission to Reiner Gamma

Landing *and roving (!)* in the heart of the Reiner Gamma swirl & anomaly

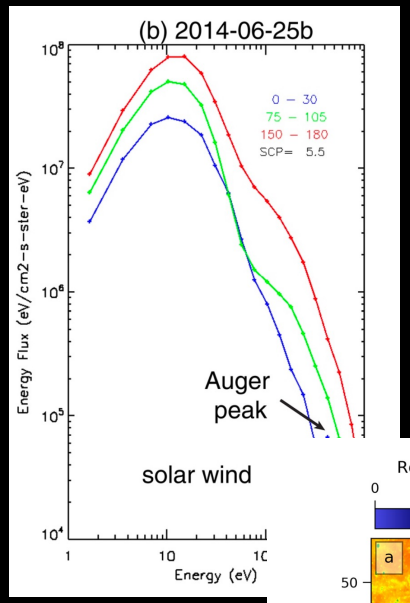


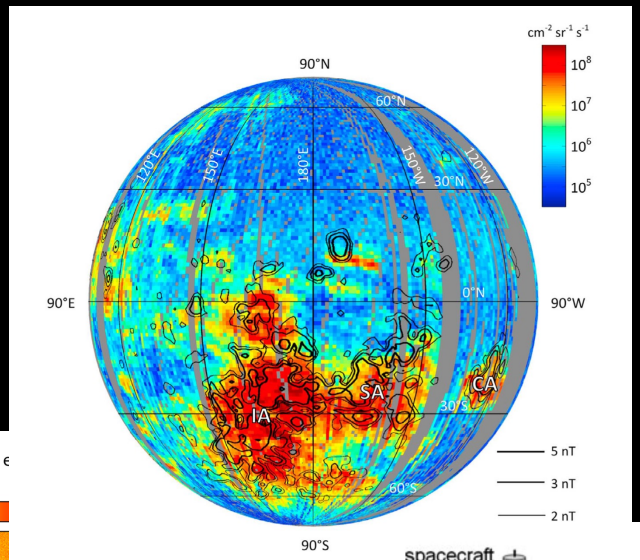


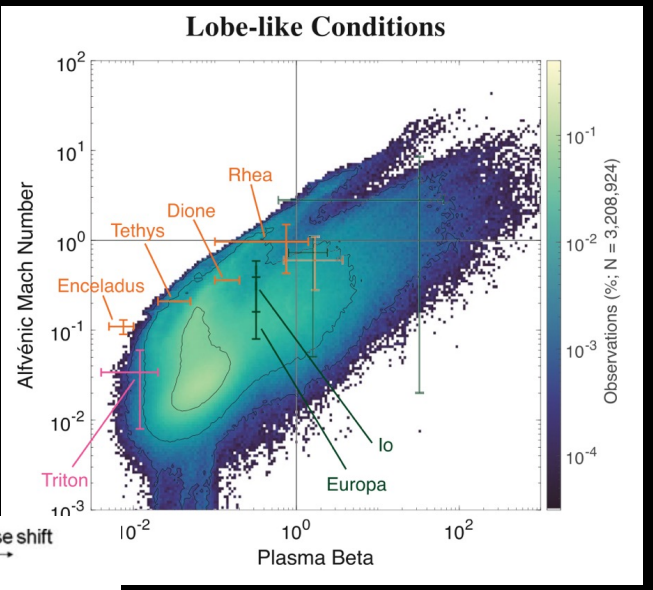


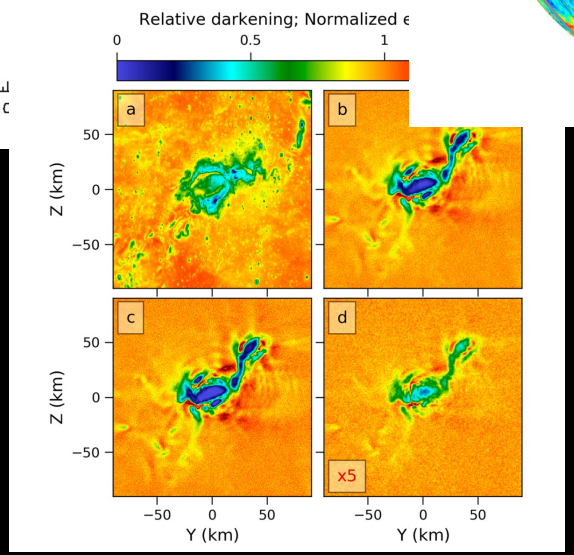
The Lunar Plasma Environment – The Big Picture

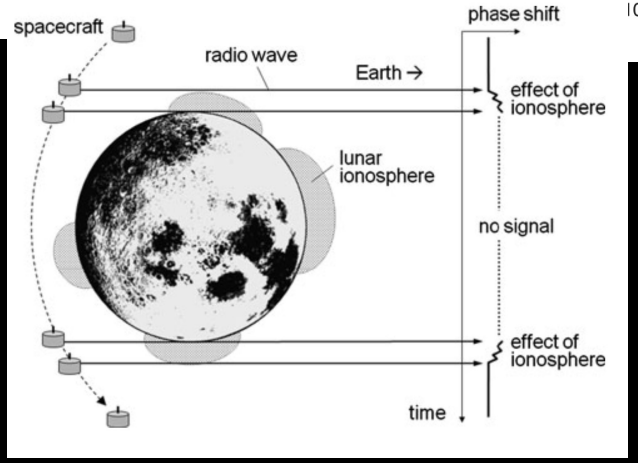
The Moon provides an accessible natural laboratory for basic and applied physical research in space sciences

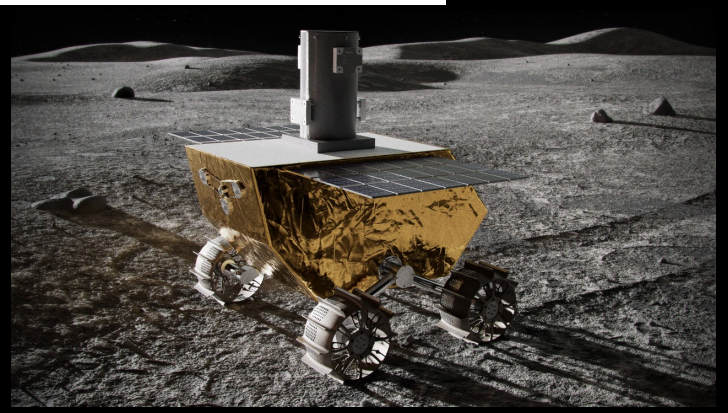












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