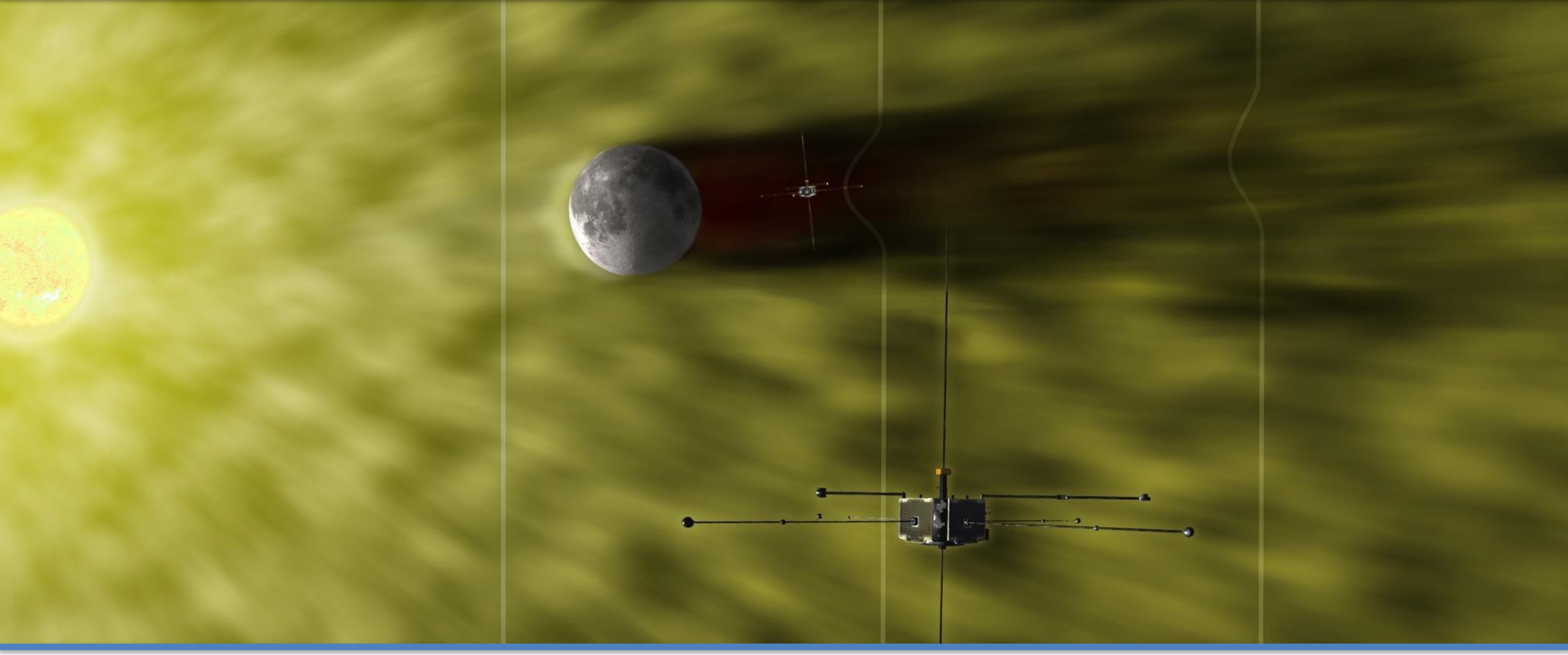

The Challenges of Performing Electromagnetic Sounding on the Moon

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Heliophysics and Planetary Science Branch

Fuqua Haviland, H., & Mittelholz, A. (in press). Probing the Lunar Interior with Electromagnetic Geophysical Methods. *Advances in Geophysics, Electromagnetic Methods.*

Fuqua Haviland, H., Delory, G. T., de Pater, I. (2019). Finite Element Analysis for Lunar Electromagnetic Sounding. *Advances in Space Research.* doi.org/10.1016/j.asr.2019.05.006

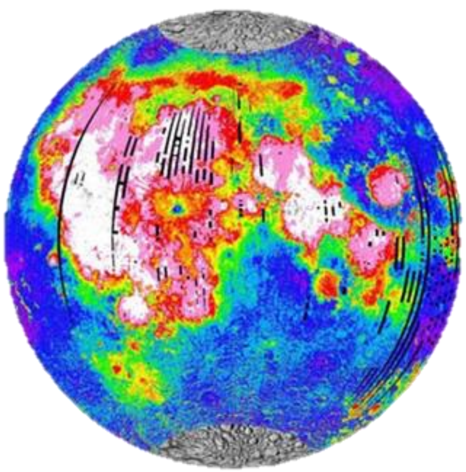
Fuqua Haviland, H., Poppe, A. R., Fatemi, S., Delory, G. T., & de Pater, I. (2019). Time-dependent hybrid plasma simulations of lunar electromagnetic induction in the solar wind. *Geophysical Research Letters*. doi.org/10.1029/2018GL080523

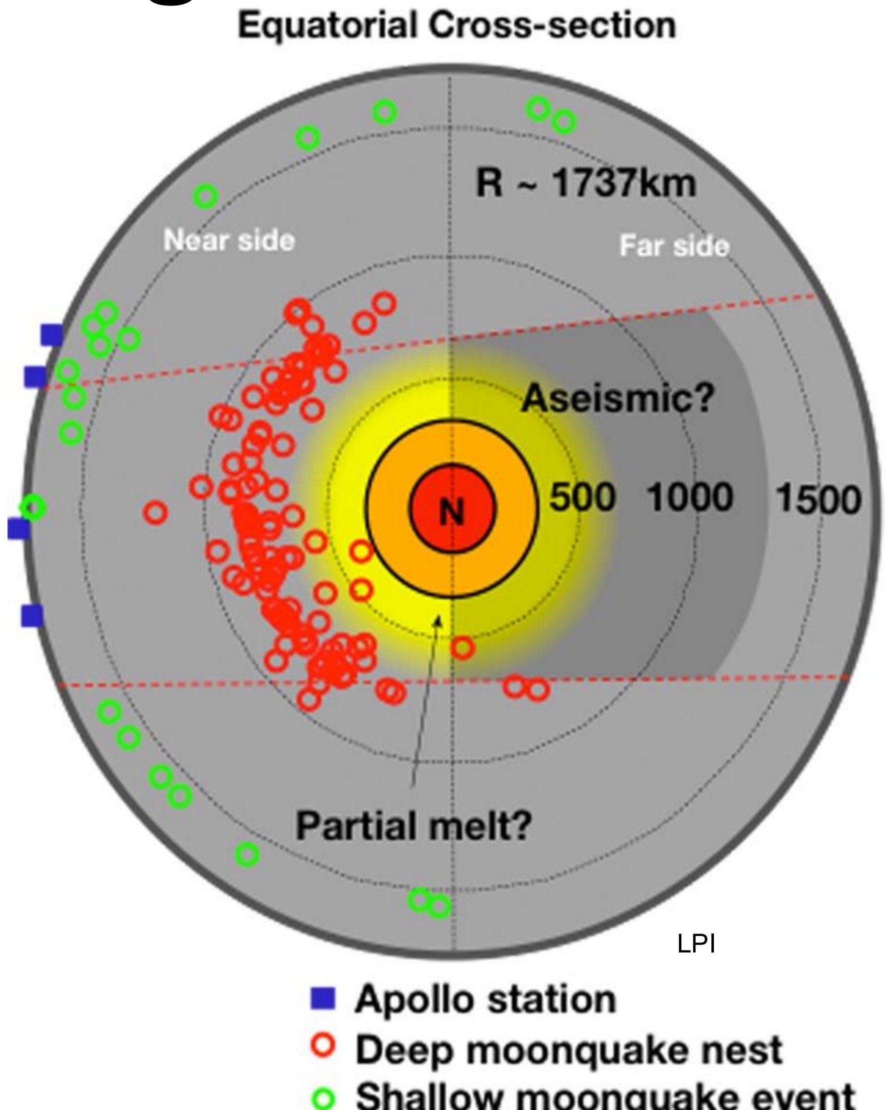
Fatemi, S., **Fuqua, H. A.**, Poppe, A. R., Delory, G. T., Halekas, J. S., Farrell, W. M., Holmström, M. (2015). On the confinement of lunar induced magnetic fields. Geophysical Research Letters, 42(17), 6931–6938. doi:10.1002/2015GL065576

Emerging work for future missions including the Lunar Geophysical Network (LGN) and Commercial Lunar Payload Services (CLPS).

Driving Science Question

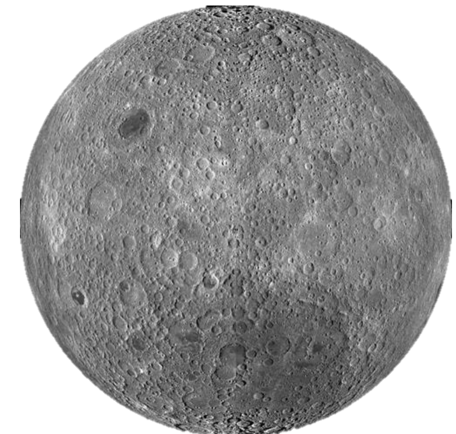
Near Side



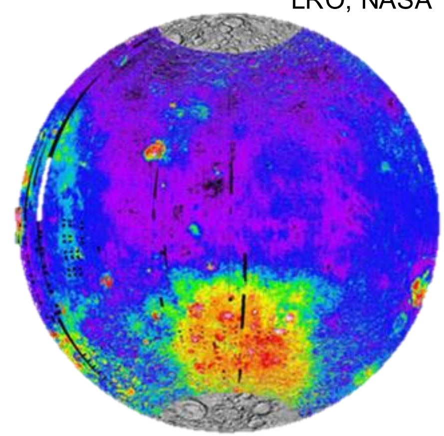


LPI

Far Side



LRO, NASA

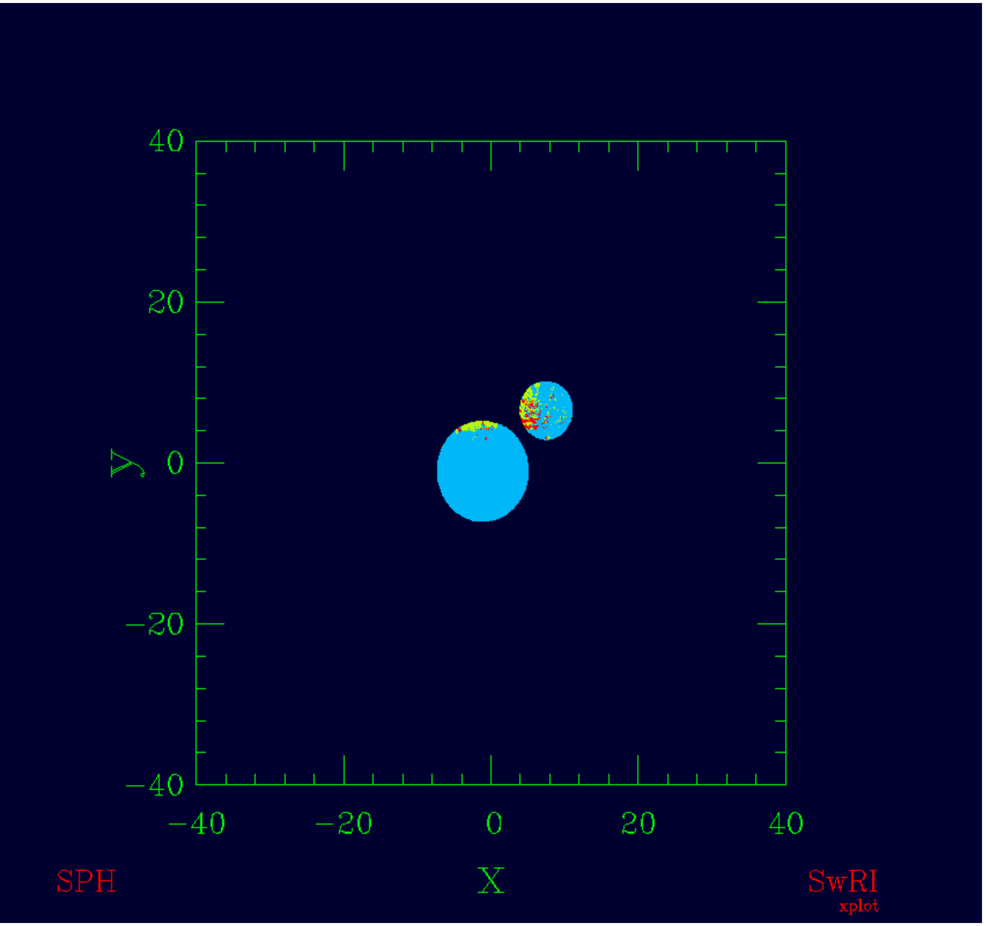


Hiesinger & Head, 2006

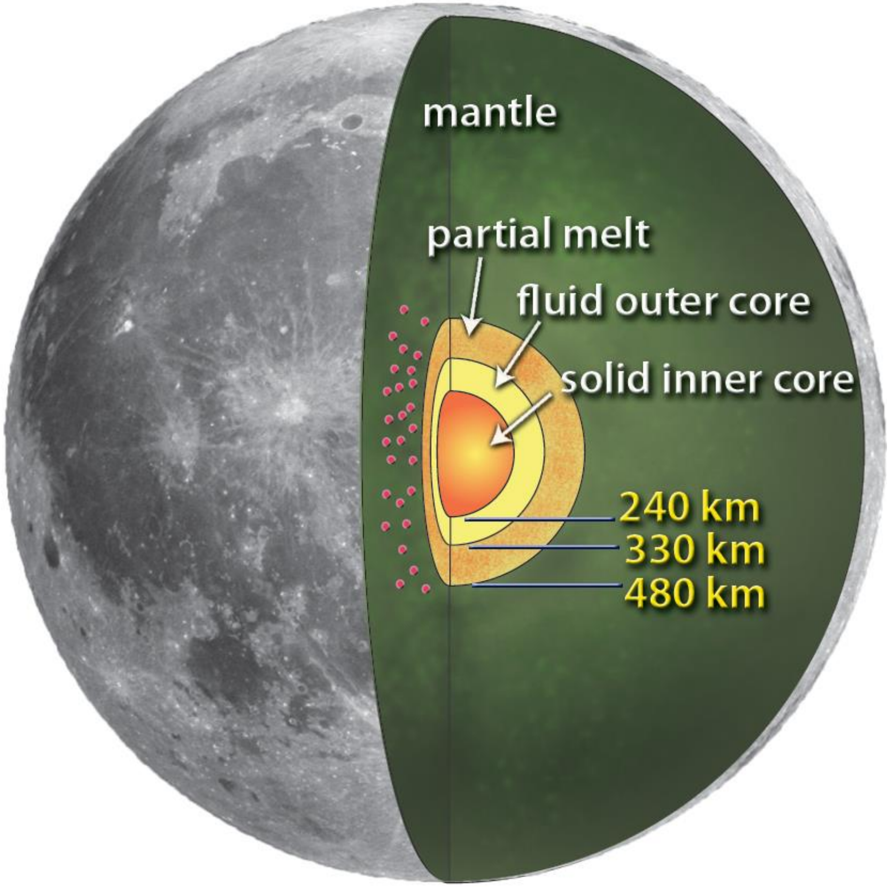
What is the current state and structure of the global lunar interior?

NASA/Marshall Space Flight Center

Lunar Origin Theories



Canup et al. 2016



Weber et al., 2011

The current state is key to constraining origin theories.

Magma Ocean Crystallization

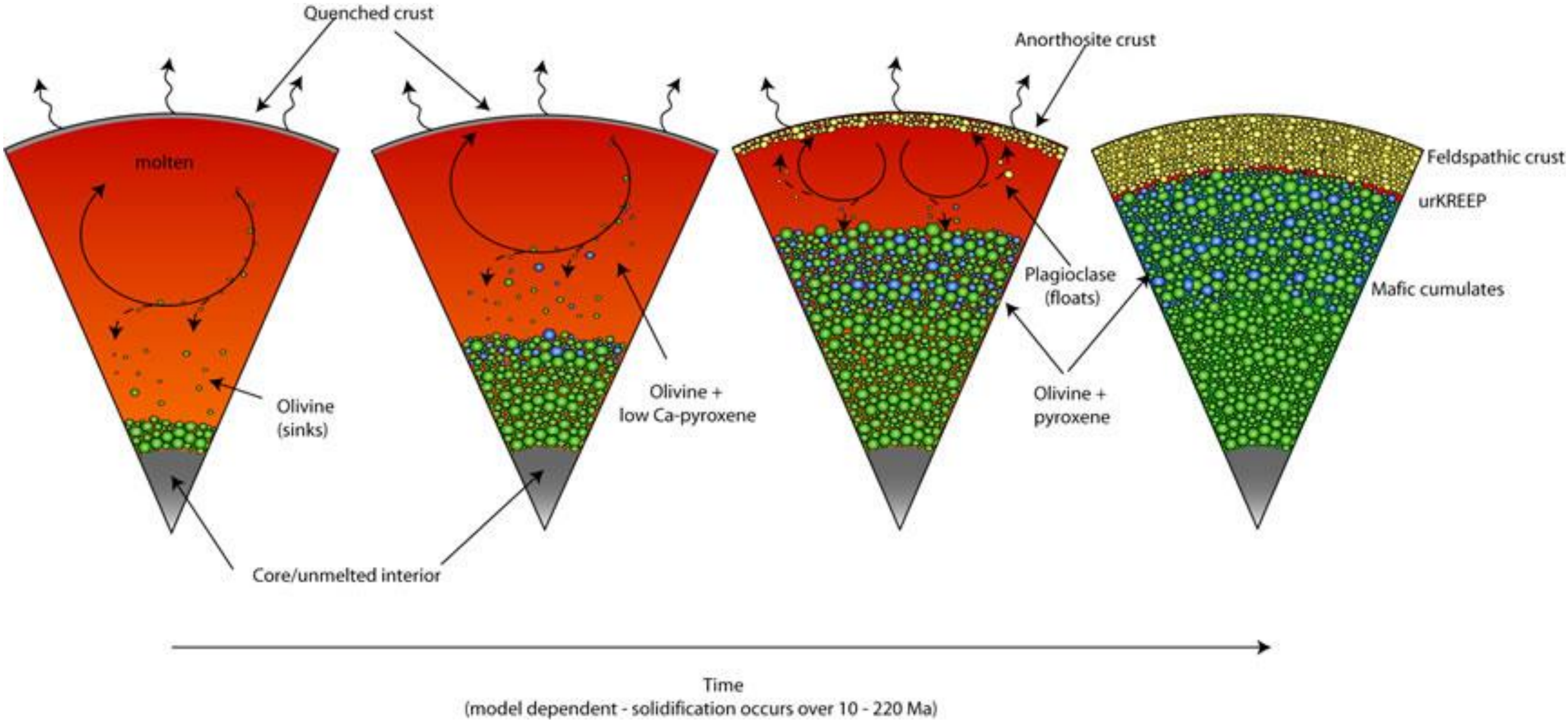
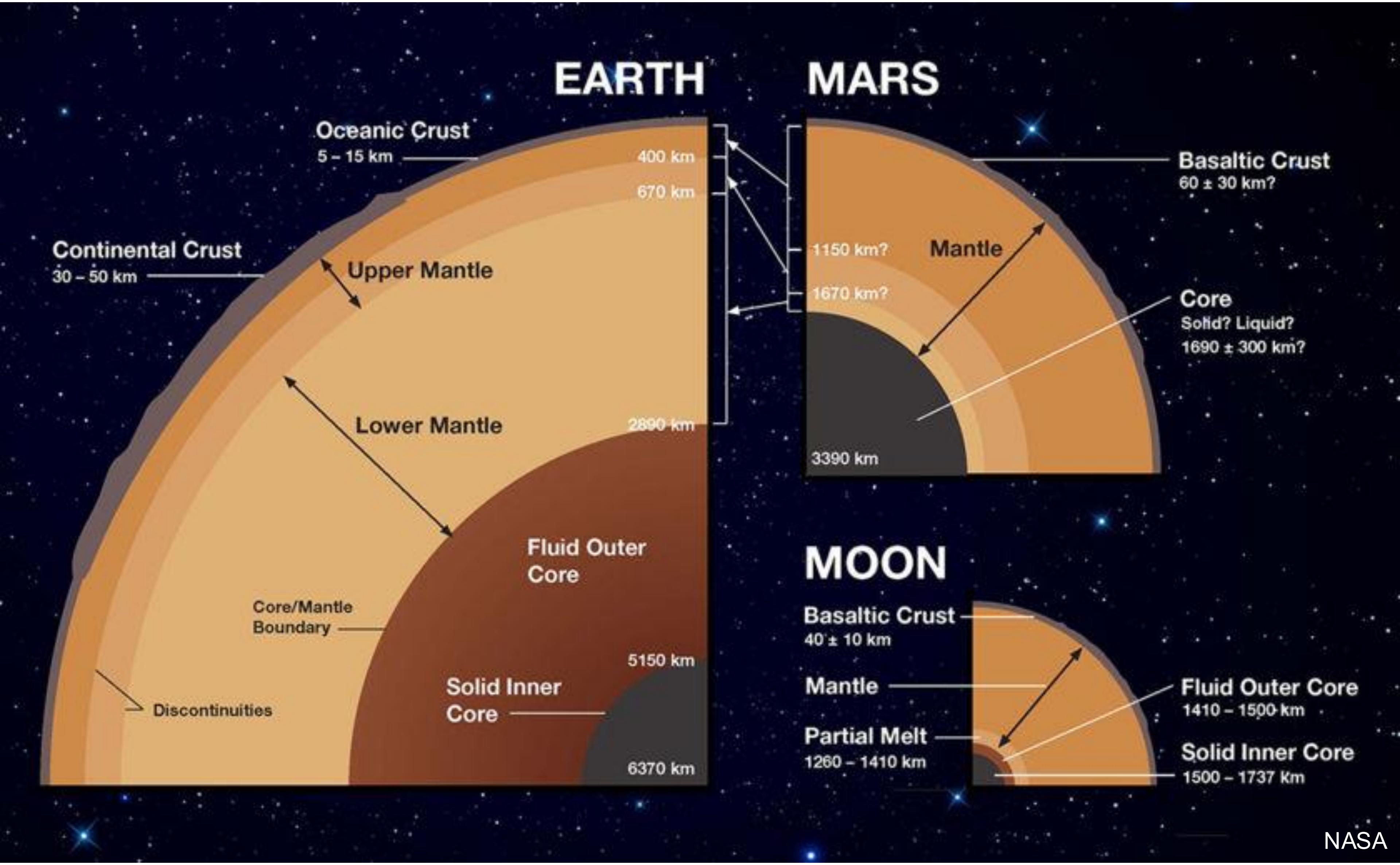


Image source: LPI

The current state of the lunar interior is the first step to constraining formation.

Terrestrial Planets Interior Structure



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Key Open Questions

1. What is the lateral and vertical extent of the Procellarum KREEP Terrain (PKT) in the upper mantle?
2. What is the global extent of the discontinuities in the upper mantle?
3. Does a partial melt region exist in the lower mantle?
4. What is the nature and extent of the lunar core?
5. How do induced magnetic fields interact with the lunar plasma environment?

EM Sounding is a powerful tool capable of constraining the electrical conductivity of the Moon, and hence, composition, temperature, and interior structure.

Sun-Earth-Moon Space Environment

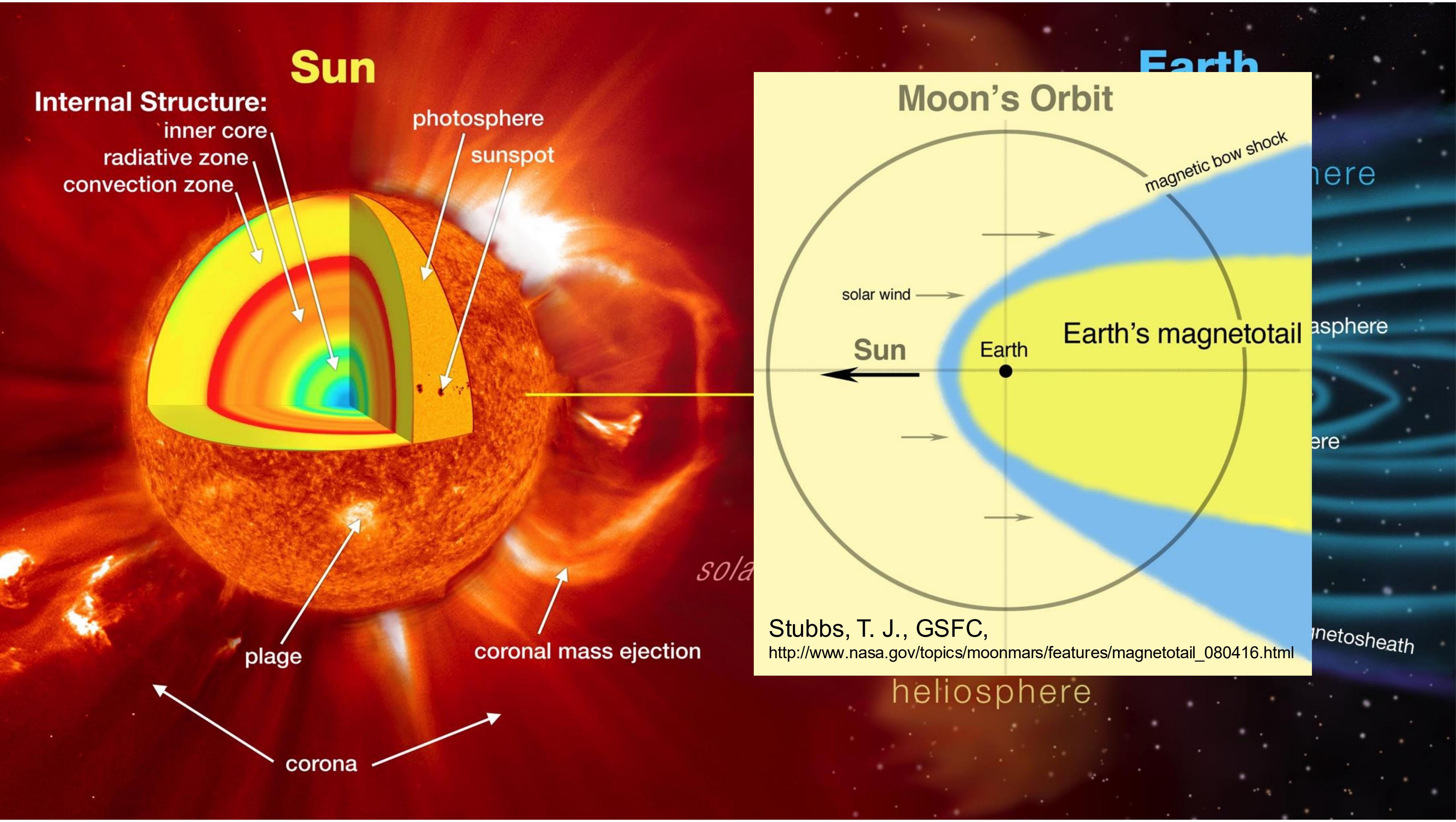
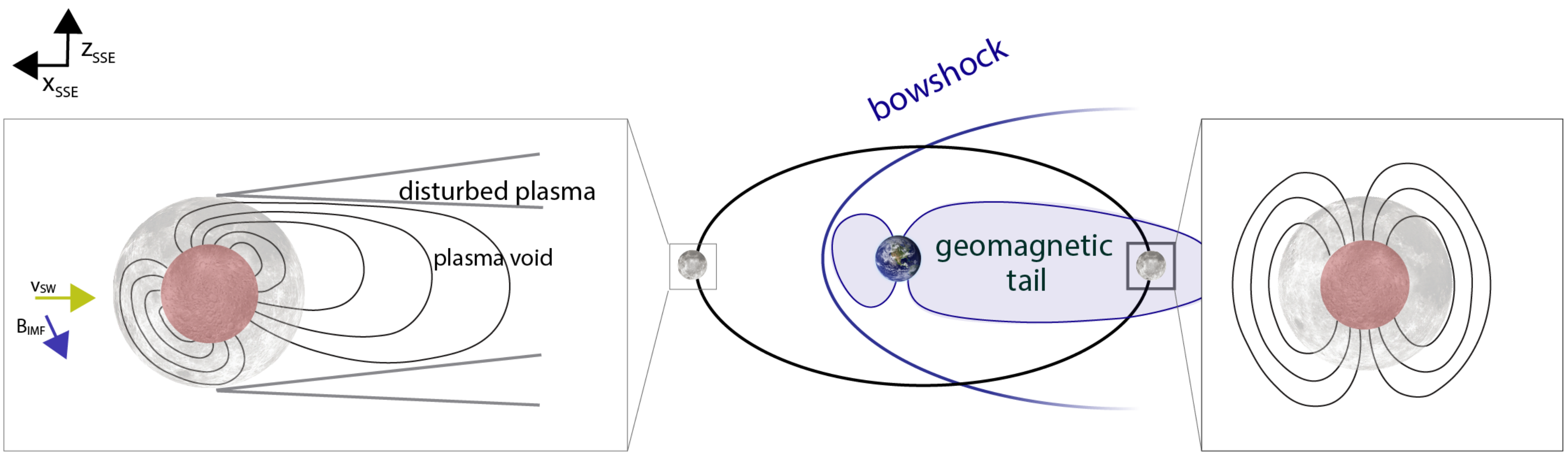


Image Source: NASA

NASA/Marshall Space Flight Center

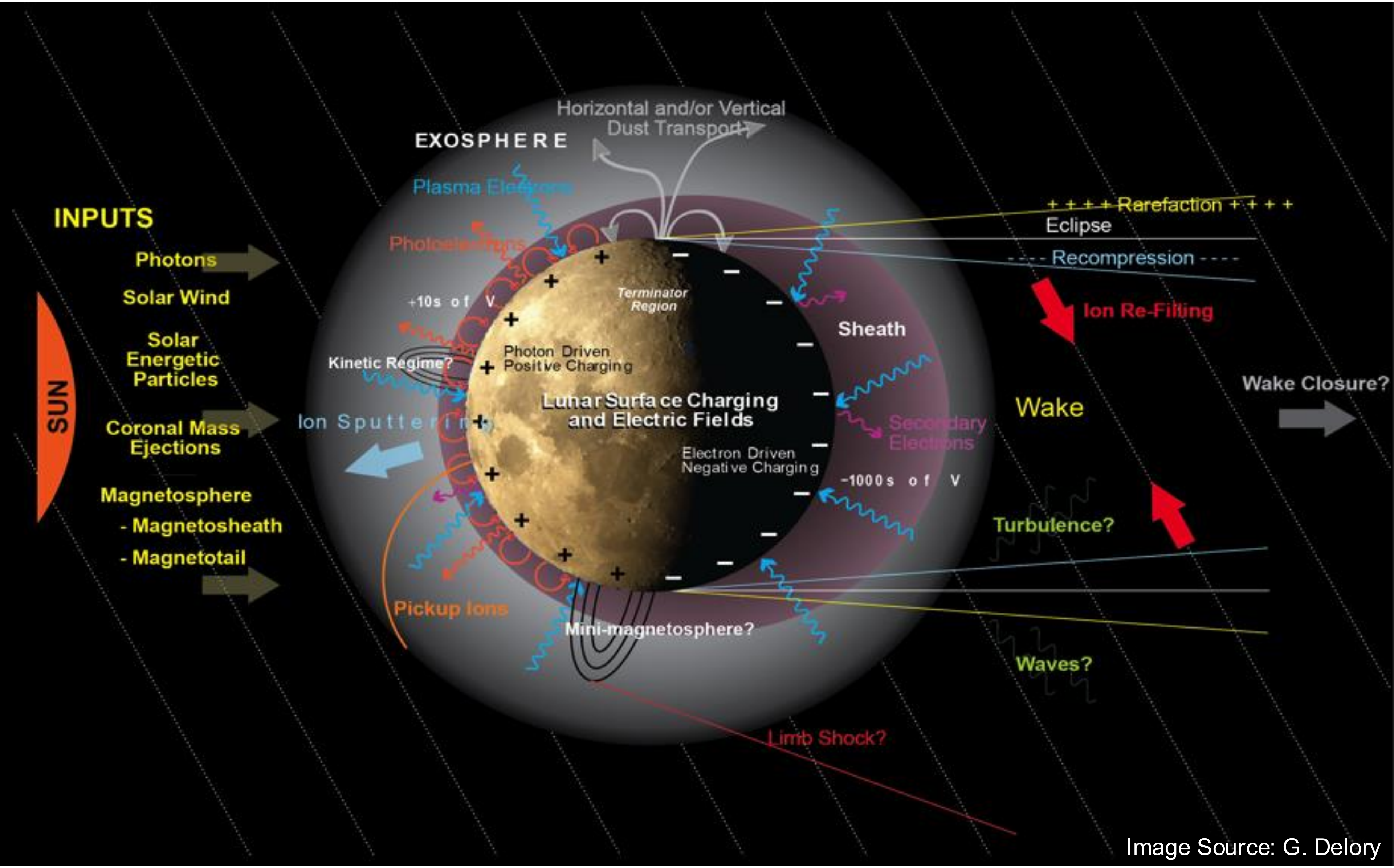
Asymmetric Induction Plasma Confinement



Fuqua Haviland & Mittelholz, in press

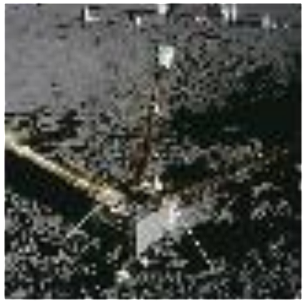
NASA/Marshall Space Flight Center

Near Surface Plasma Processes



Lunar Magnetometers


Explorer 35


Apollo Lunar Surface Magnetometer


Lunar Prospector


Kaguya Selene


Lunar Magnetotelluric Sounder

Parameter:	ALSM	X35	ASubsat	LP	KS	LMS
Ranges (nT)	±200 ±100 ±50	A:±200,±60,±20 G:±64,±24	15:±200,±50 16:±100,±25	±65,536	±64 ±256 ±1,024 ±65,536	±1,024 ±65,536
Resolution (nT)	0.1,0.2,0.4	A:0.2,0.6,2.0 G:0.094,0.25	15:1.6,0.4 16:0.8,0.2	0.002	0.002, 0.008, 0.03, 2	
Absolute Accuracy (nT)						$\pm 1 + 1\%\|B\|$
Sampling rate (Hz)	3	A:0.05 G:5	0.04,0.08	16	32	
Average Power (W)	3.5	A:0.7 G:1.1	0.7	4.5[1]		6.1
Mass (kg)	8.9	A:2.4 G:2.7	1.0	5[1]	14[1]	3.51
Operation Duration	A12:11/1969-06/1970 A15:07/1971-06/1974 A16:04/1972-10/1977	A:11/1969-06/1970 G:11/1969-12/1969	A15:08/1971-04/1972 A16:04/1972-05/1972	01/1998-07/1999	10/2007-06/2009	03/2025
Nominal Altitude (km)	surface	9390 x 2570	100	100	100	surface
Extended Periapsis (km)				15-30	30	
Induction Studies	MTF[2]	MTF	MTF	Global TF	Global TF	MT
Error Sources	Heaters, offset, shadow drift A15:A/D converter malfunction A16:digital spurious signal	Sensor drift, gain and offset degradation Transient anomalies		pointing error		
Data Availability	NSSDCA ID:1969-099C-04[3]	A:NSSDCA ID:1967-070A-03 G:NSSDCA ID:1967-070A-04		Acuna [2024]	PDS:SLN-L-LMAG[4]	upcoming on PDS
Instrument Description	Dyal et al. [1970]	A:Sonett et al. [1968] G:Ness [1970]	Coleman Jr et al. [1972a,b]	Lin et al. [1998]	Takahashi et al. [2009]	Grimm et al. [2021]

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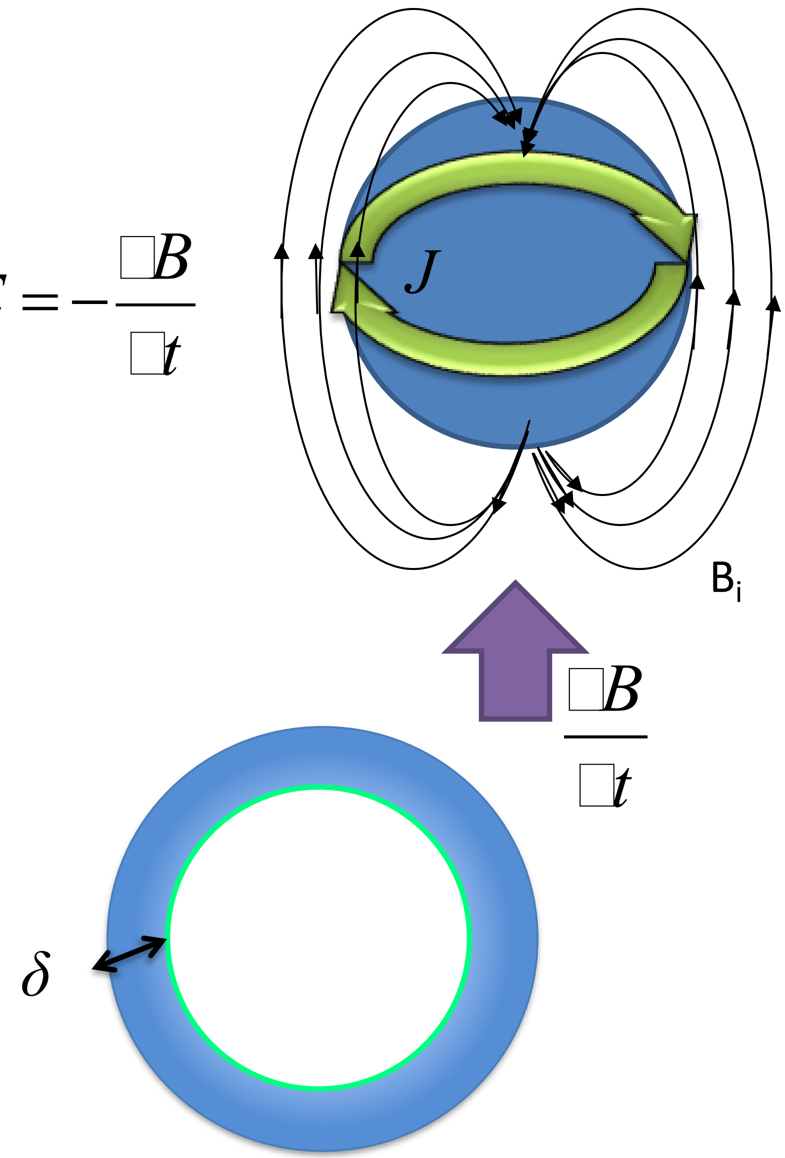
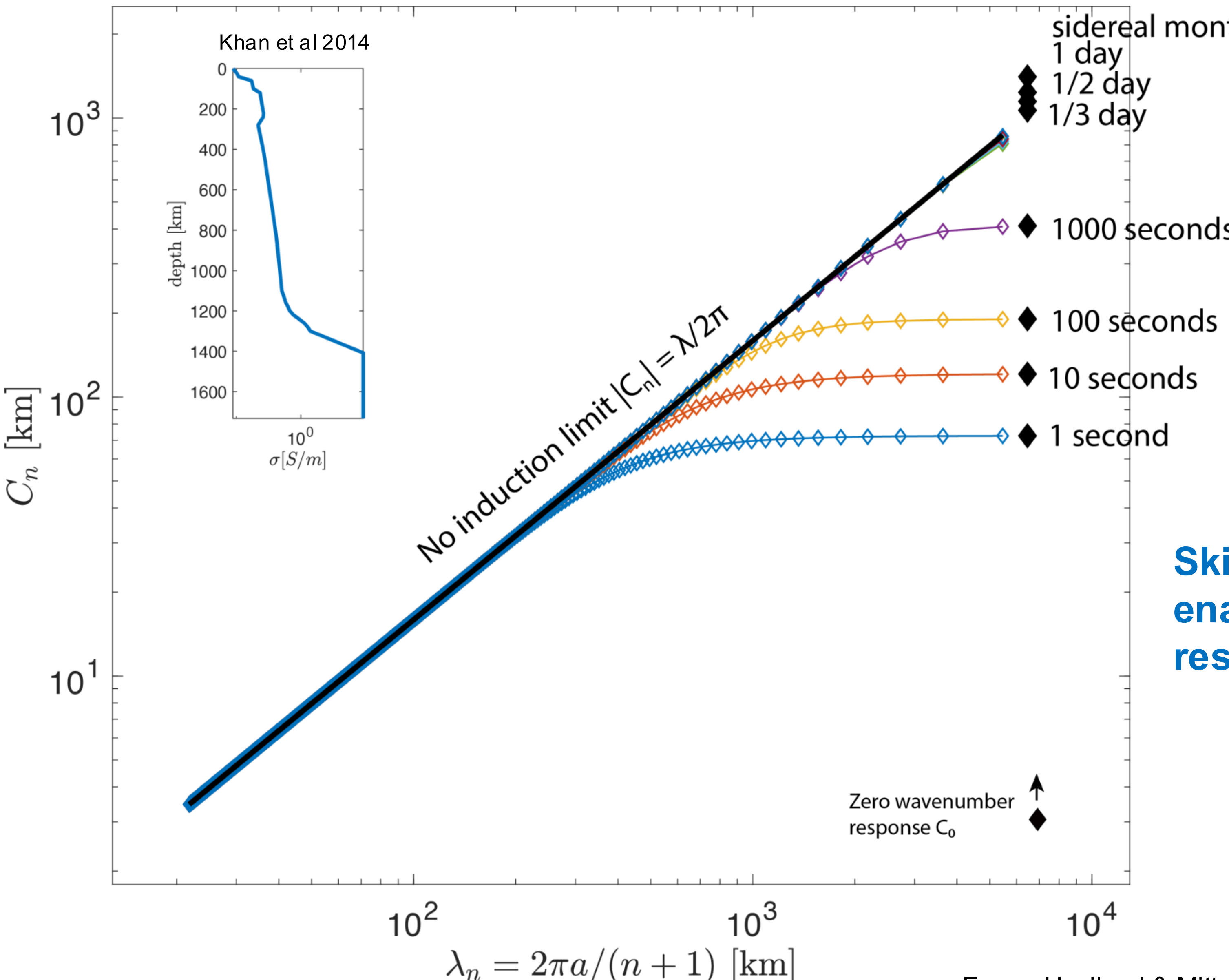
Physical Laws

- Maxwell's Equations
  - Faraday's Law of Induction: $\nabla \times E = -\frac{\partial B}{\partial t}$
  - Ampere's Law: $\nabla \times B = \mu_o J$
- Ohm's Law: $J_f = \sigma E$
- Diffusion Equation: $\nabla^2 B = \sigma \frac{\partial B}{\partial t}$
- Skin Depth: $\delta \propto (\sigma f)^{-1/2}$



Lunar EM Sounding Periods

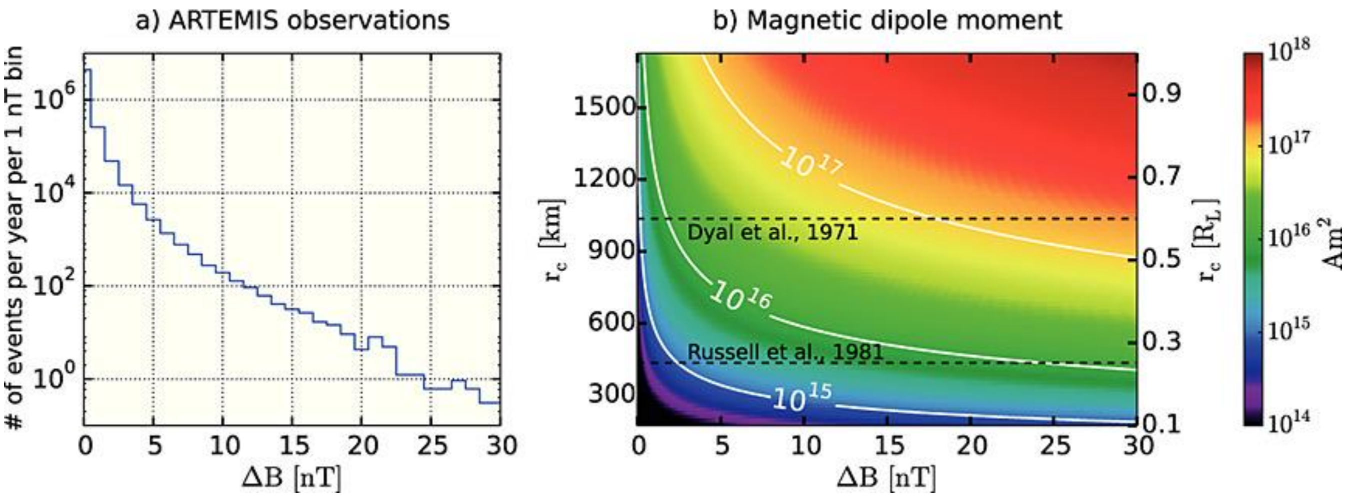


C_n=total C response

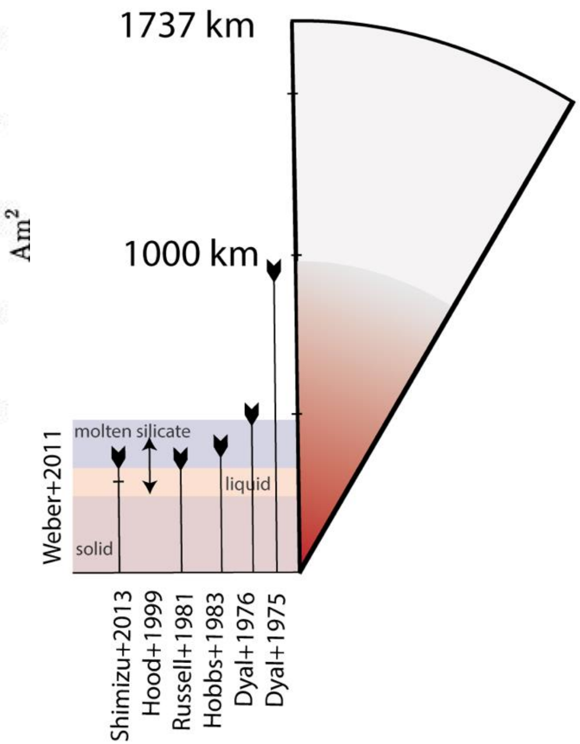
Skin depth enables depth resolution

Fuqua Haviland & Mittelholz, in press

Solar Wind Transients



Fatemi et al 2015



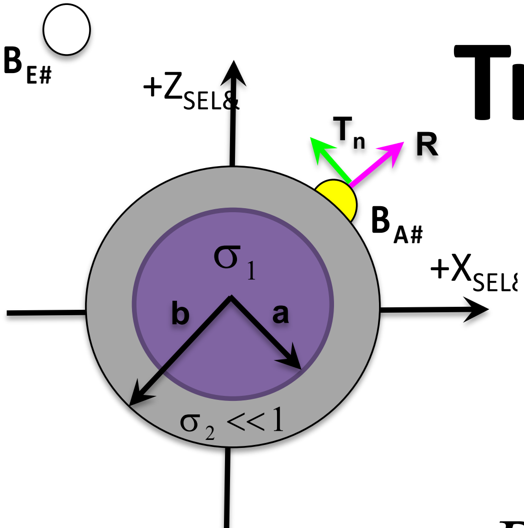
Large transient events can be used for EM Sounding.

Core size and magnitude of transient event size induced magnetic moment.

Summary of Core sizes from EM Sounding analyses.

Fuqua Haviland & Mittelholz, in press

Time Domain EM Sounding Transient Analysis

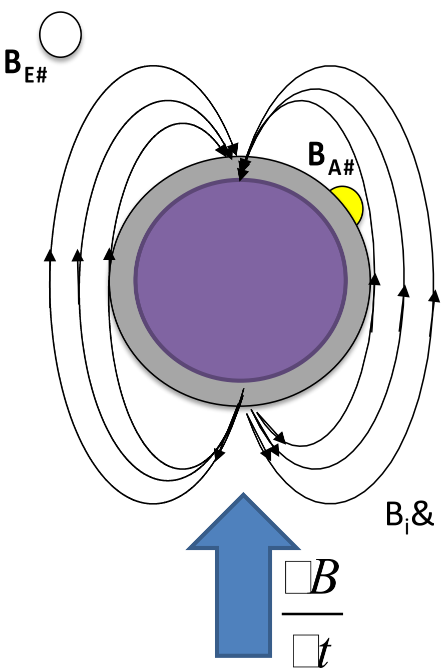


$$B_{AR} = -3\left(\frac{a}{b}\right)^3 \Delta B_{Er} F(t) + B_{Erf}$$

$$B_{ATe,n} = \frac{3}{2}\left(\frac{a}{b}\right)^3 \Delta B_{Ei} F(t) + B_{Eif}$$

$$\Delta B_{Ei} = B_{Eif} - B_{Eio}, for \;\; i = r, e, n$$

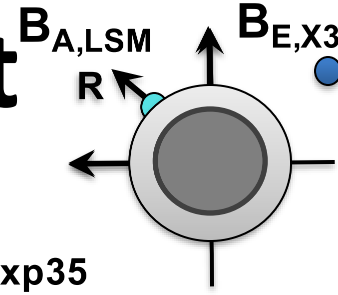
$$F(t) = \frac{2}{\pi^2}\sum_{s=1}^{\infty}\frac{1}{s^2}\exp\left(\frac{-s^2\pi^2 t}{\mu_o \sigma_1 a^2}\right)$$

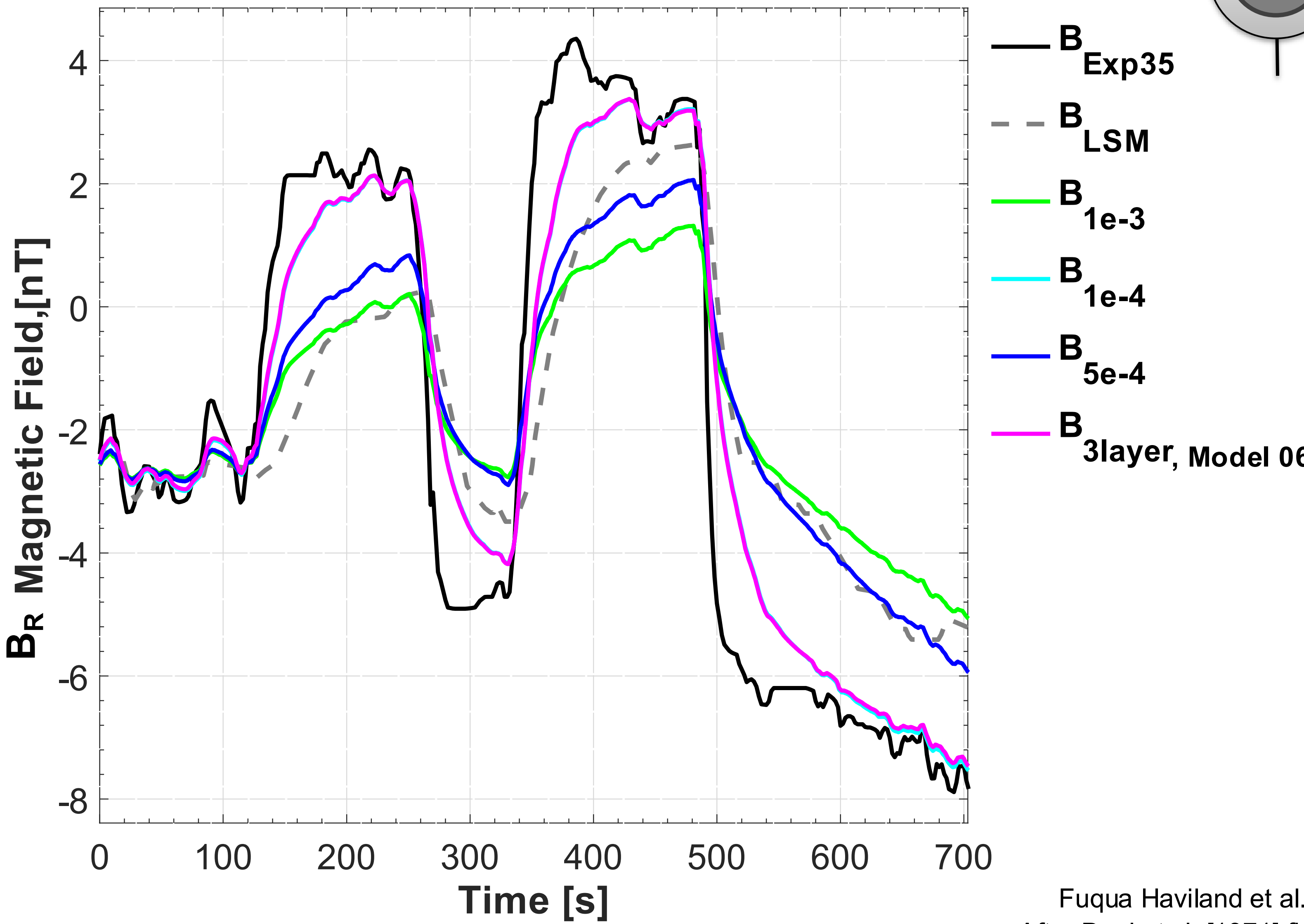


Dyal & Parkin, 1971

Fuqua Haviland et al., 2019. ASR.

Case Study: Apollo Event





Fuqua Haviland et al., 2019
After Dyal et al. [1971] figure 10

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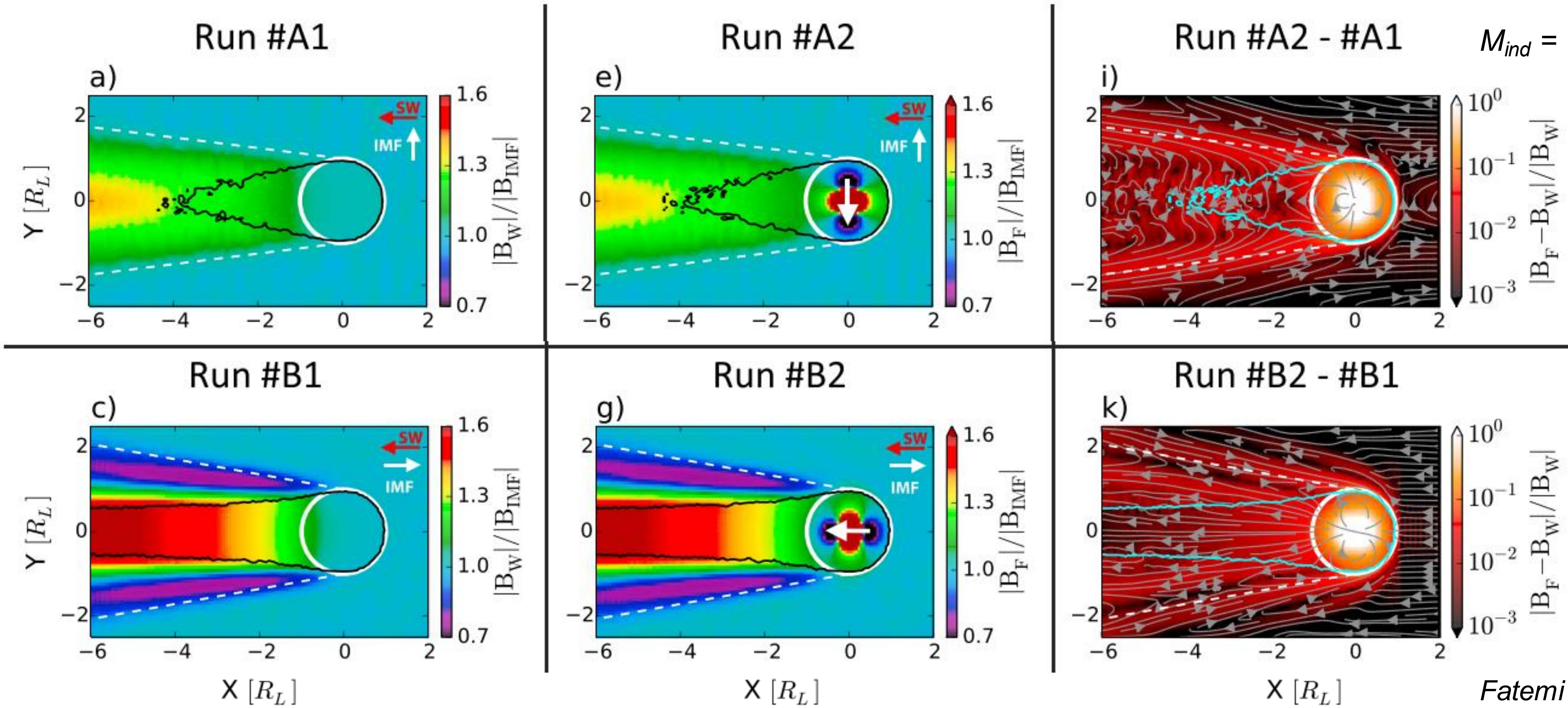
Static Hybrid Model Results



M_{ind} = 10^16 A m^2

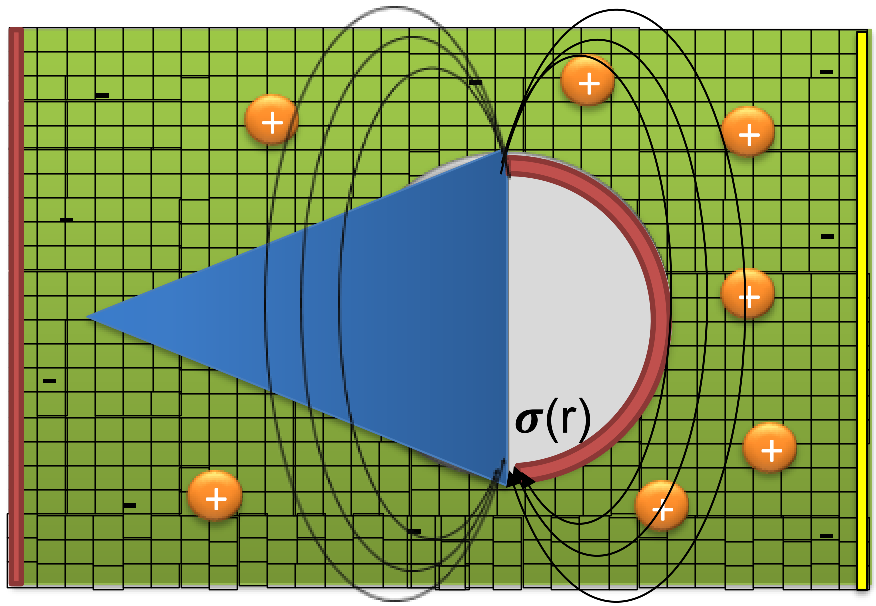
Fatemi et al., [2015]

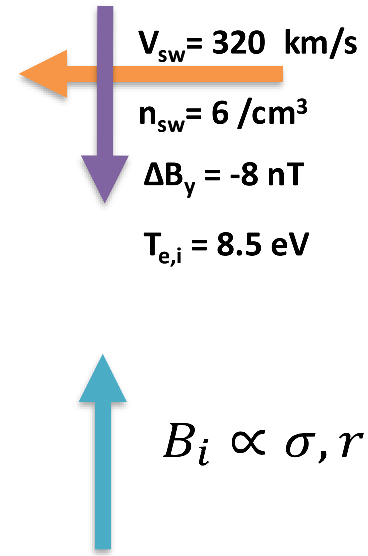
Dayside confinement, as predicted. Nightside fields are not confined within wake cavity. Strong induced field signatures in the deep wake near surface, especially with large IMF changes.

Transient Plasma Hybrid Kinetic Induction Model

General SW Case, Perpendicular

AMITIS, Fatemi et al.,2017

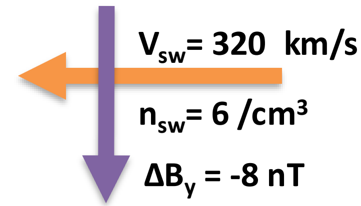


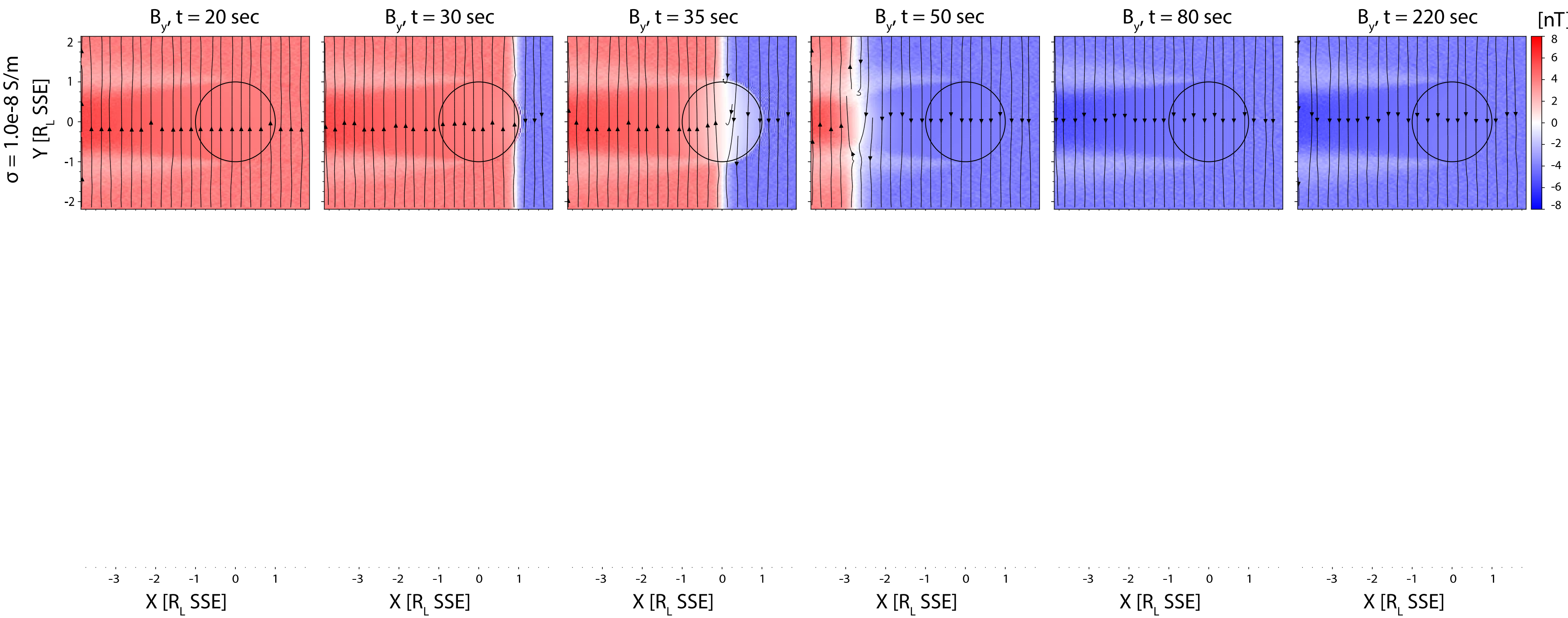


- Cell size: 50 km (~0.028 R_L)
- 16 macroparticles (only protons) per cell
- t_{step} = 0.001 s
- 0 < t < ~300 s, t=24 s IMF discontinuity
- $\boldsymbol{\sigma}_1$ = 1.0 e – 8, 1.0 e – 4, 1.0 e – 3 [S/m]
- At t=0, B_{IMF} = [0, +4, 0] nT
- At t=24s, B_{IMF} = [0, −4, 0] nT
- ΔB_y = -8 nT
- $\boldsymbol{\sigma}_{VAC}$ = 2.0 e – 7 [S/m]

- Conducting radius (r_1) = 1,600 km (~ 0.91R_L, or ~ 32 cells), ~M_{ind} = 1.64 e 17 A m^2 (Fatemi et al., 2015; Saur et al., 2010).
- Resistive crust (1e-8 S/m) radius = 150 km (~3 cells crust). R_L=1750 km.
- Model captures inductive and plasma response self-consistently
- SSE Coordinate System: Selenocentric Solar Ecliptic (+X_{SSE} points towards the sun)

Results: Time Dependence

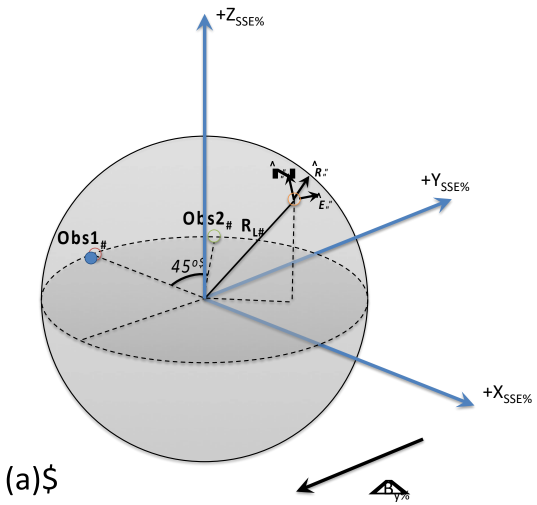


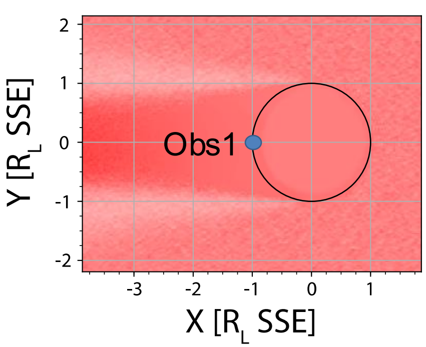


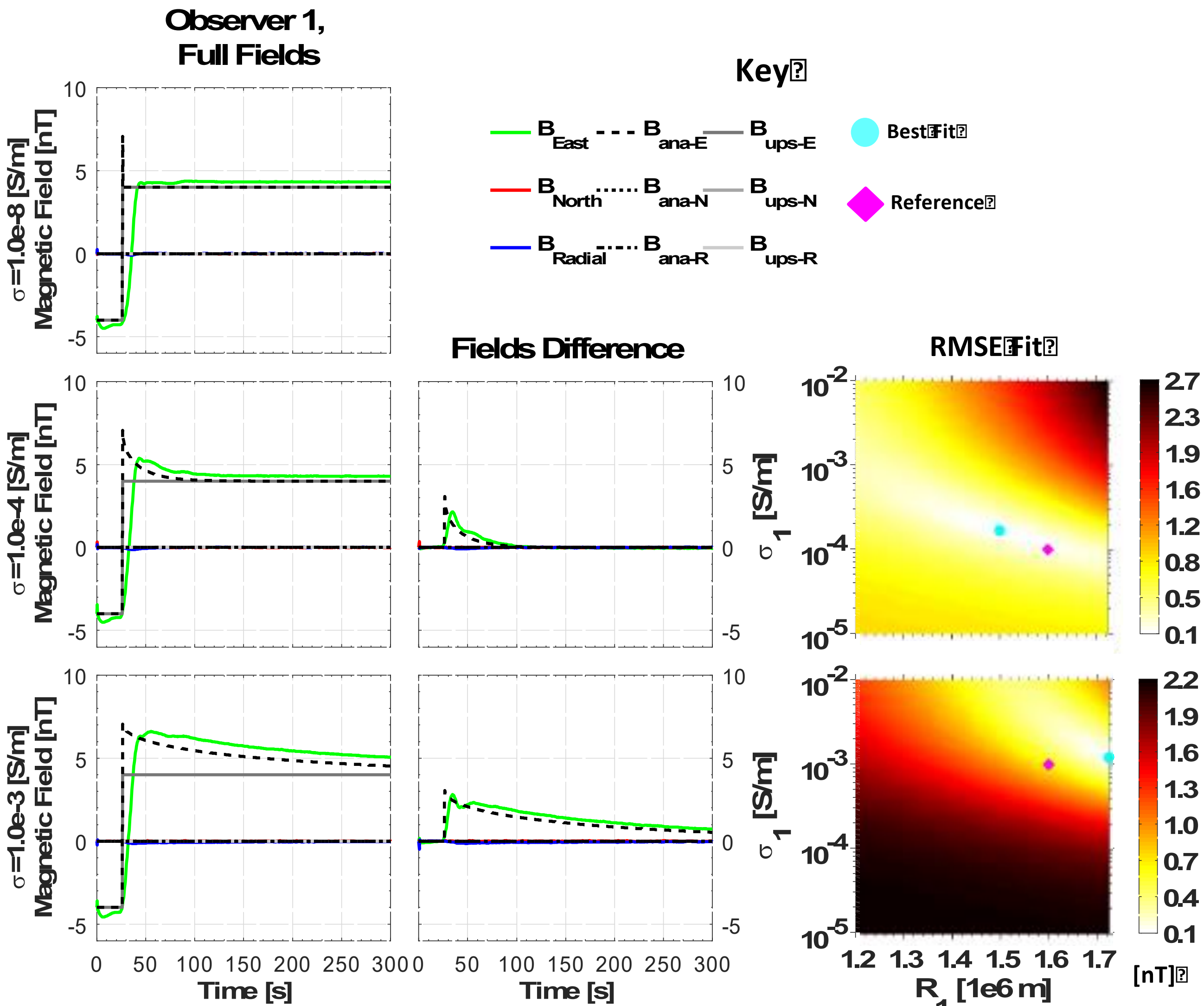
SSE Coordinate System (+X_{SSE} points towards the sun)
R_L=1850 km

Fuqua Haviland et al., 2019. GRL.

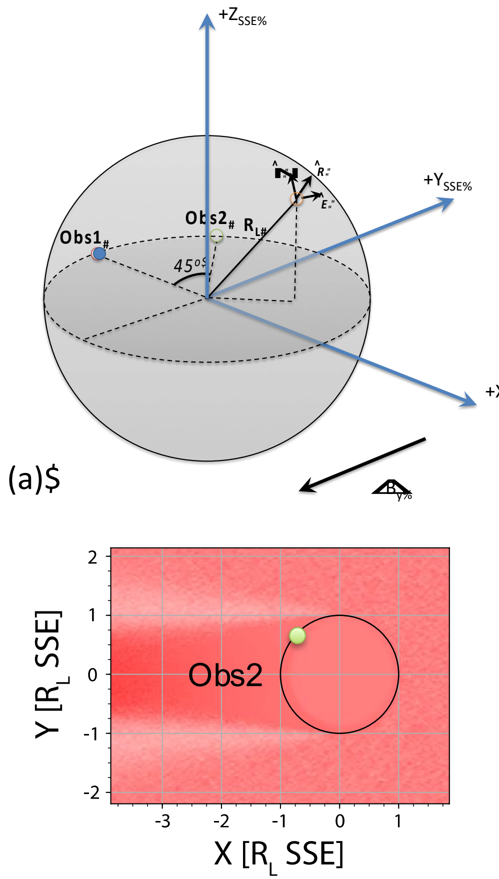
Results: Case Study 1 Time Series

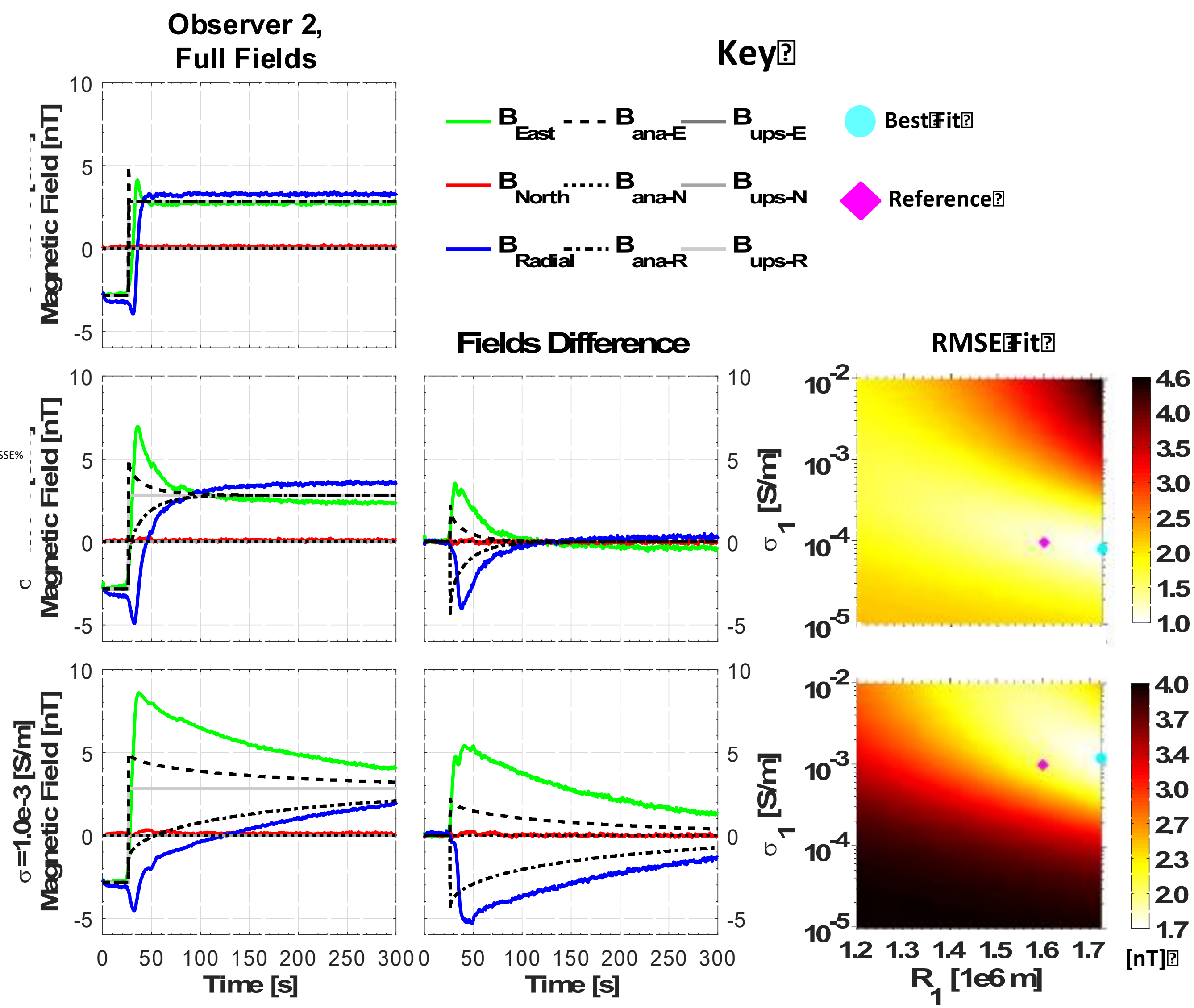




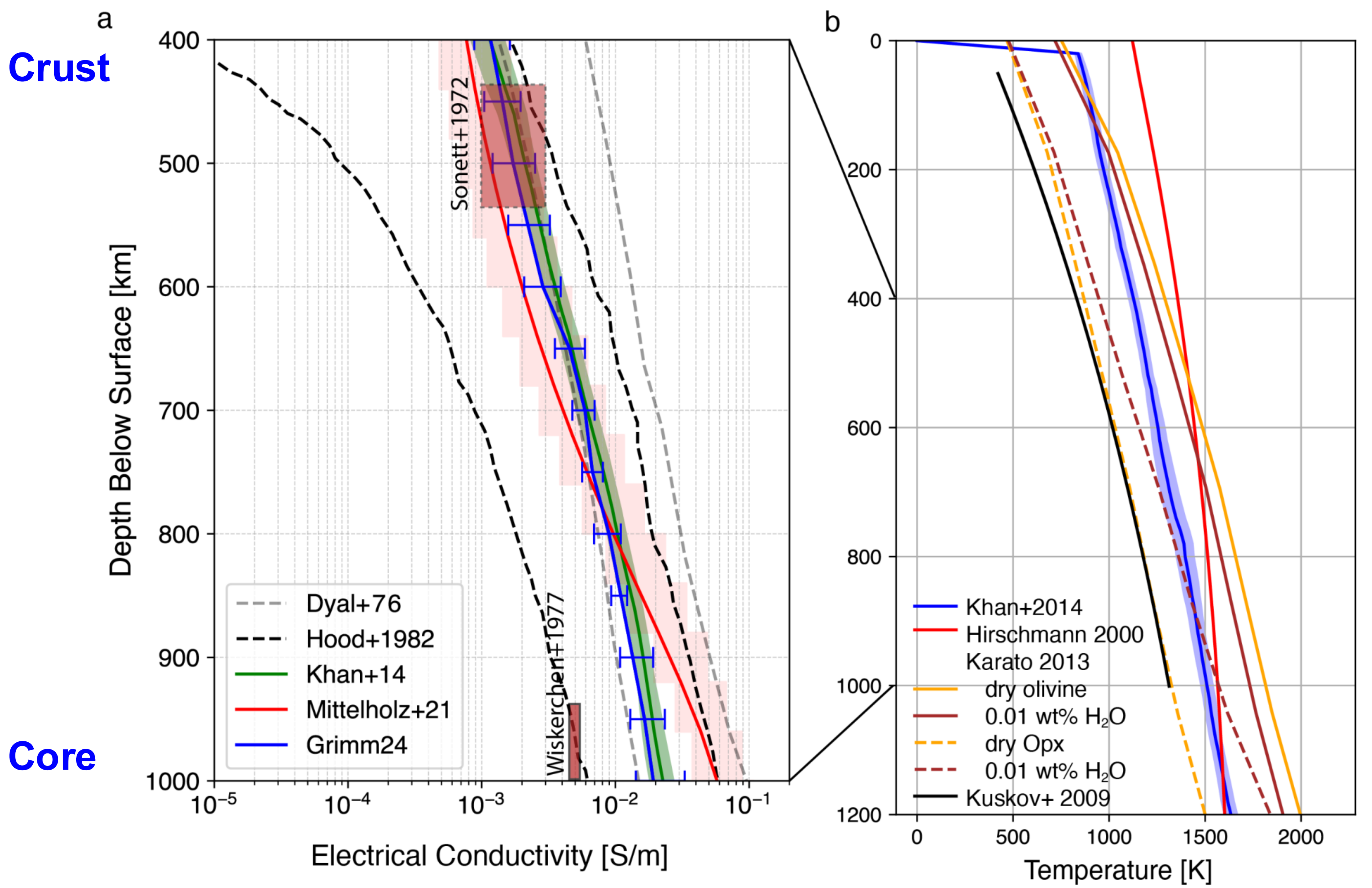


Results: Case Study 2 Time Series



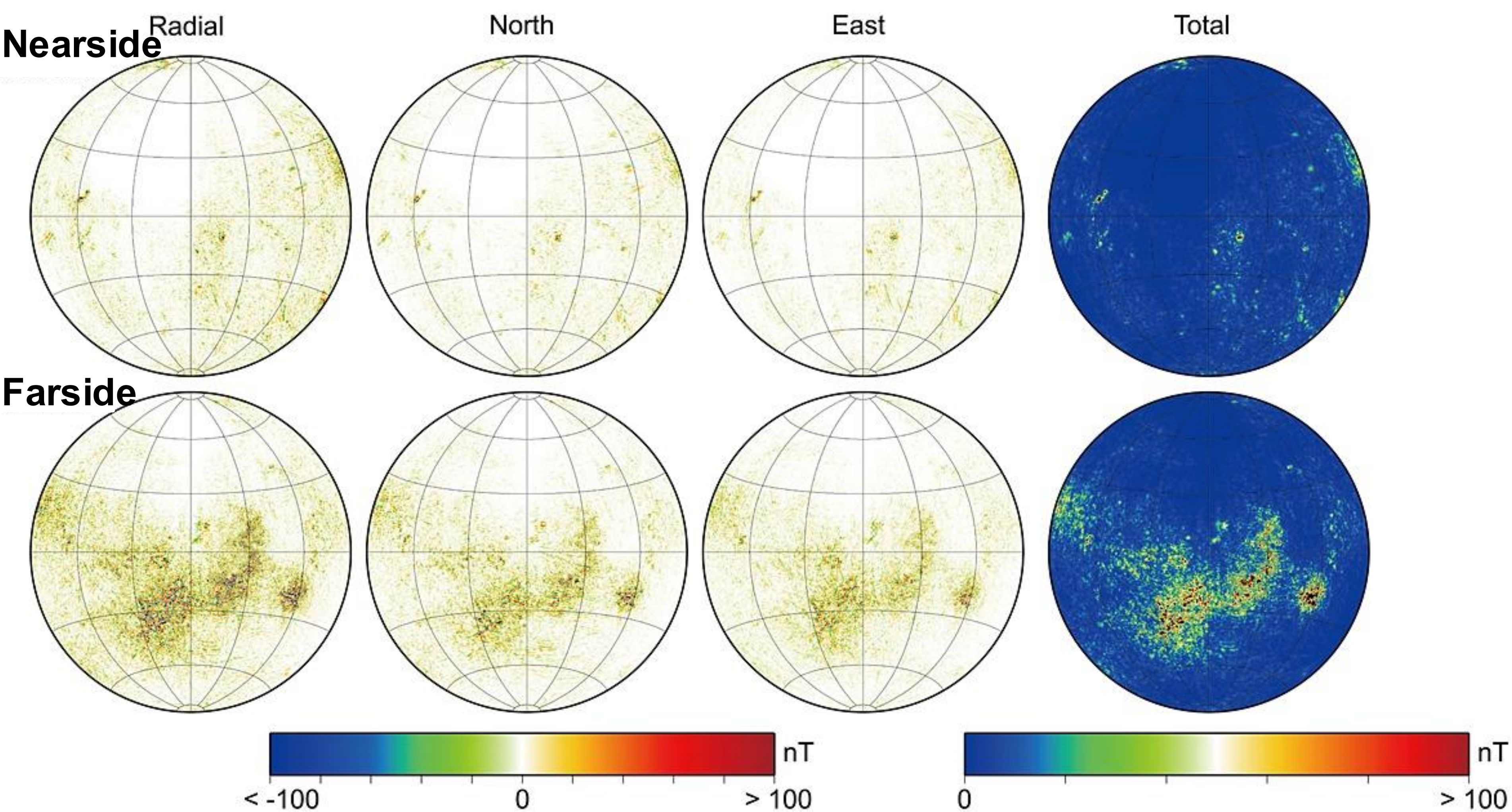


Electrical Conductivity & Temperature Profiles



Fuqua Haviland & Mittelholz, in press

Lunar Crustal Magnetic Fields



Tsunakawa et al., 2015, JGR-P

Regions of weak crustal fields are prevalent.

Surface magnetic field components and total intensity.

NASA/Marshall Space Flight Center

Apollo Uncompressed Magnetic Fields

Table 2. Summary of lunar surface remanent magnetic field measurements.

Site	Coordinates, deg.	Field Magnitude, Gammas	Magnetic-field components, gammas		
			Up	East	North
Apollo 16:					
ALSEP Site	8.9°S, 15.5°E	234 ± 3	-181 ± 3	-57 ± 3	$+136 \pm 2$
Site 2		189 ± 5	-189 ± 4	$+3 \pm 6$	$+10 \pm 3$
Site 5		112 ± 5	$+104 \pm 5$	-5 ± 4	-40 ± 3
Site 13		327 ± 7	-159 ± 6	-190 ± 8	-214 ± 6
LRV Final Site		113 ± 4	-66 ± 4	-76 ± 4	$+52 \pm 2$
Apollo 15 ALSEP Site	26.1°N, 3.7°E	3.4 ± 2.9	3.3 ± 1.5	0.9 ± 2.0	-0.2 ± 1.5
Apollo 14:	3.7°S, 17.5°W				
Site A		103 ± 5	-93 ± 4	$+38 \pm 5$	-24 ± 5
Site C′		43 ± 6	-15 ± 4	-36 ± 5	-19 ± 8
Apollo 12 ALSEP Site	3.2°S, 23.4°W	38 ± 2	-25.8 ± 1.0	$+11.9 \pm 0.9$	-25.8 ± 0.4

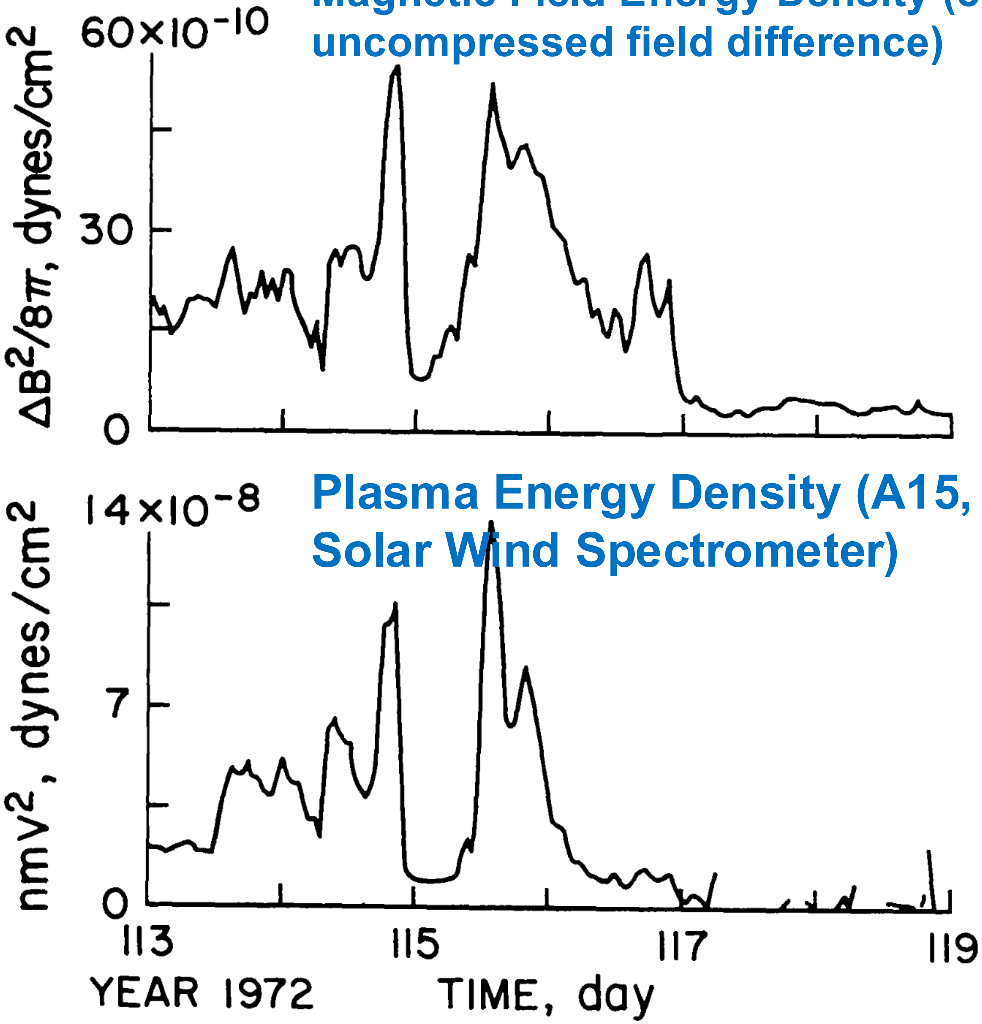
Descartes 1 nT at 100 km orbit, and 327 nT at the surface, (Magnetic fields fall off at r^-3)

Dyal et al 1973

Field Interactions with Solar Wind

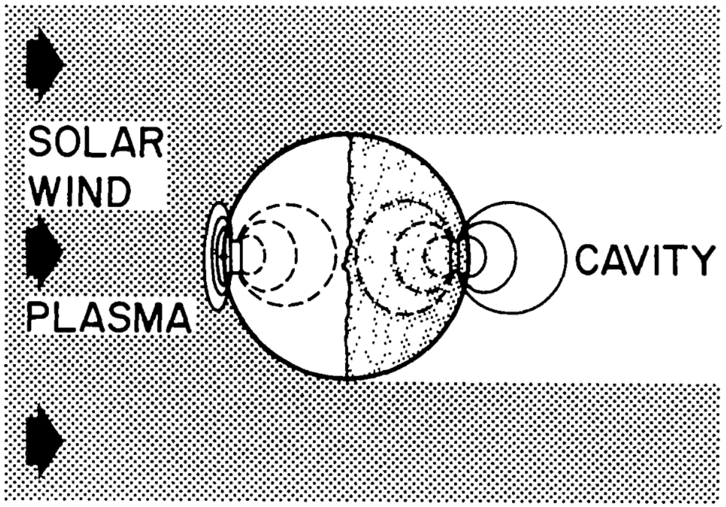
Magnetic Field Energy Density (compressed, uncompressed field difference)

Plasma Energy Density (A15, Solar Wind Spectrometer)



Dyal et al 1972

Scale Size: A12, 2 < L< 200 km
A16, 5 < L< 100 km



A16 observed a compression of the crustal field as a function of solar wind pressure.

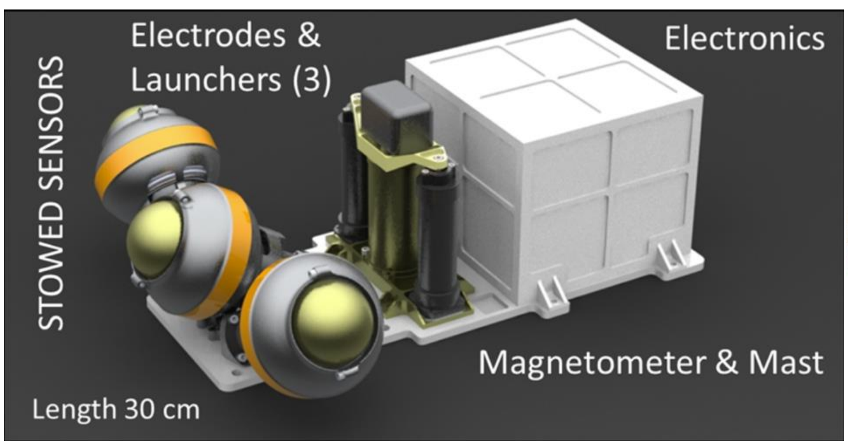
Dyal et al 1973

Lunar Geophysical Network (LGN)

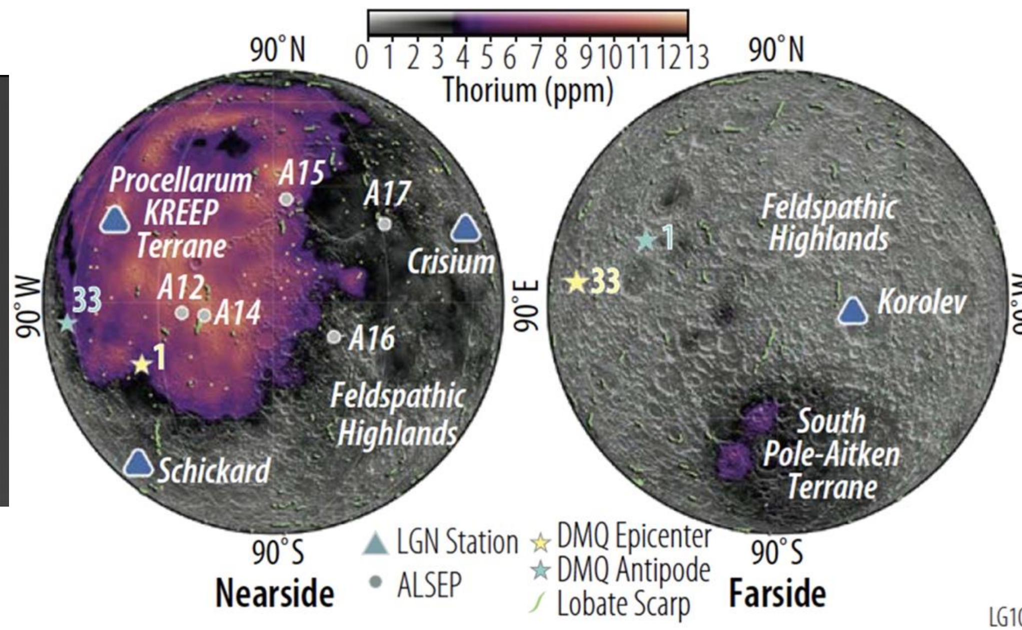
Mission Objectives: to improve the state of knowledge of the lunar interior in terms of composition, structure, temperature.

Project Description: The LGN will be composed of a network of ~4 stations with one farside station and communications orbiter. Each lander containing next generation instruments.

Funding: Preliminary Mission Concept Study NASA SMD Planetary Science Decadal Survey Update.



CPLS Lunar Magnetic Sounder, Neal et al. 2020, PMCS



Fuqua Haviland et al, 2022, PSJ

NASA/Marshall Space Flight Center

Firefly Blue Ghost 1 Lunar Magnetotelluric Sounder

Mission Duration: March 2-16, 2025
346 hours daylight, 5 hours night

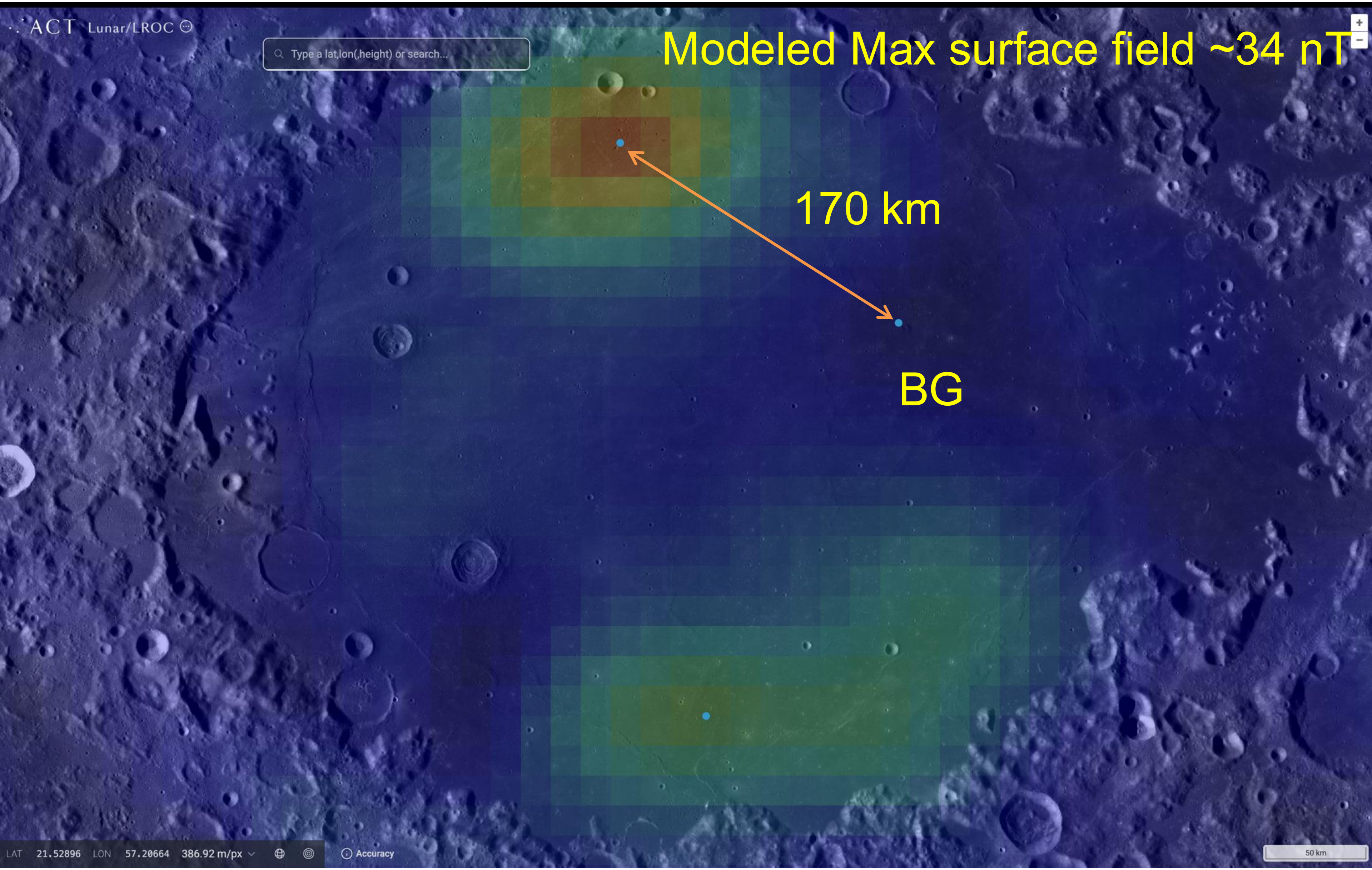
Firefly

LMS Deployment: https://www.youtube.com/watch?v=je8sHHizhuw

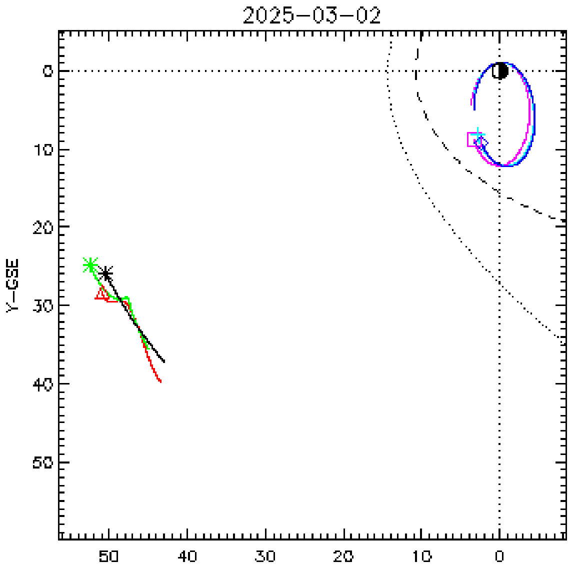
NASA/Marshall Space Flight Center

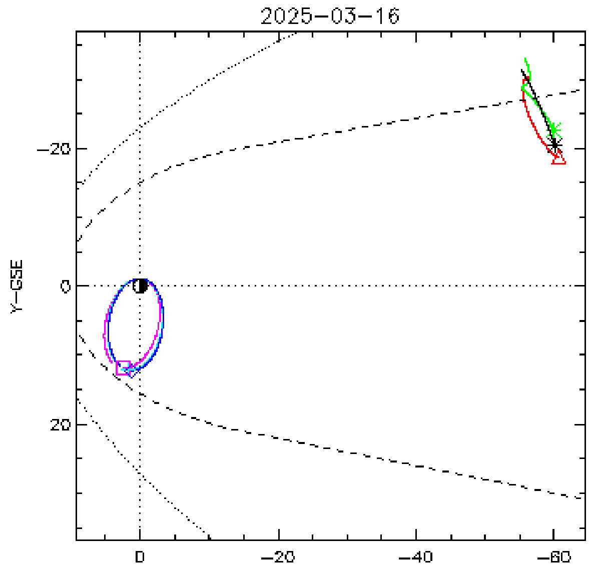
Firefly Blue Ghost 1 LMS Mare Crisium

Mare Crisium Crustal Magnetic Fields



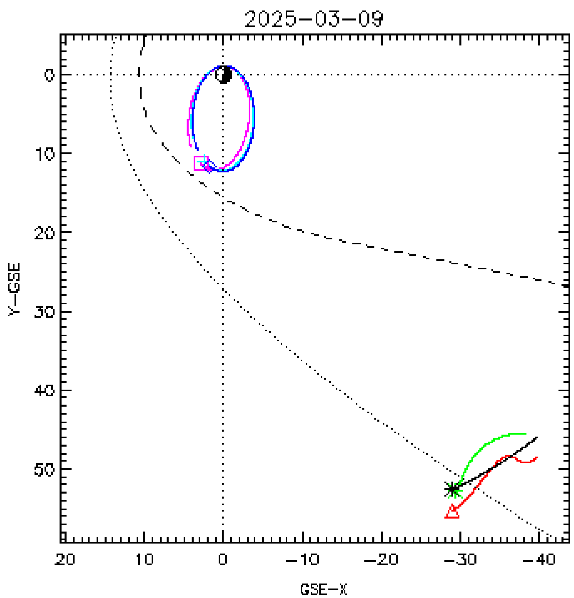
Firefly Blue Ghost 1 Plasma Regime

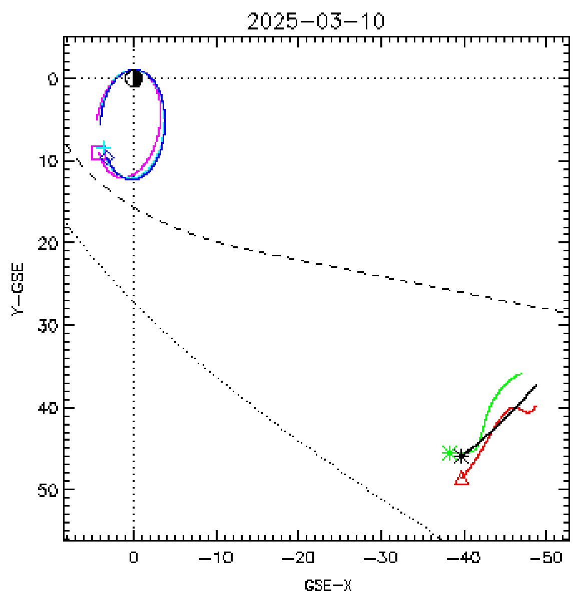


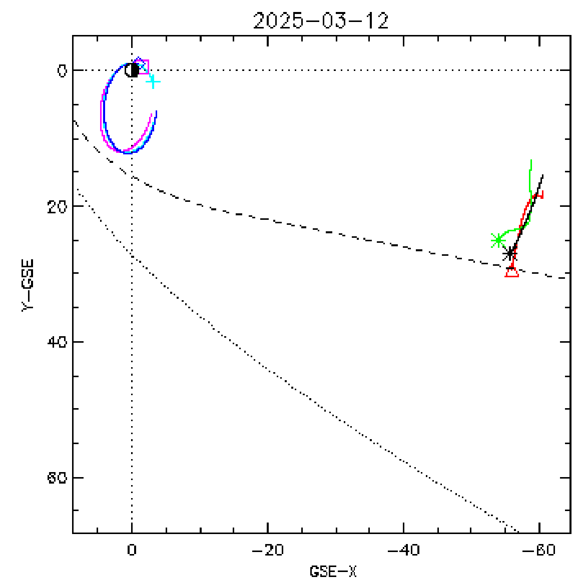


Final orbits:
THEMIS−P1 (B)
THEMIS−P2 (C)
THEMIS−P3 (D)
THEMIS−P4 (E)
THEMIS−P5 (A)

Line Styles:
BowShock: Dot
Magnetopause: Dash
Neutral Sheet (XZ):
Dash−Dot (AEN mod)
t=interval midpoint





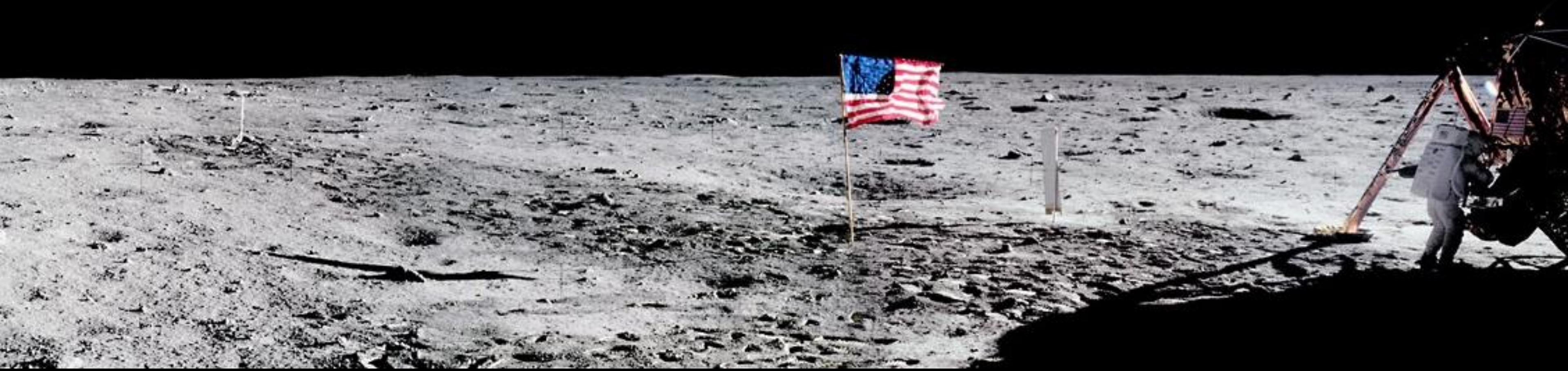


https://artemis.ssl.berkeley.edu/

Conclusion & Future Work

- EM Sounding is capable of providing insights into important geophysical methods constraining the electrical conductivity, composition, and temperature of the Moon.
- Plasma environment is important context for correctly interrupting EM geophysical fields.
- Gaps remain in current analyses including the unavailability of some Apollo datasets.
- Additional work is needed to isolate induction with magnetometer observations (Apollo, Lunar Prospector, Kaguya, THEMIS-ARTEMIS, KPLO, LMS, LITMS).
- Future magnetometer observations at or near the surface of the Moon will improve electrical conductivity constraints, and knowledge of the current state of the lunar interior.

Questions?



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