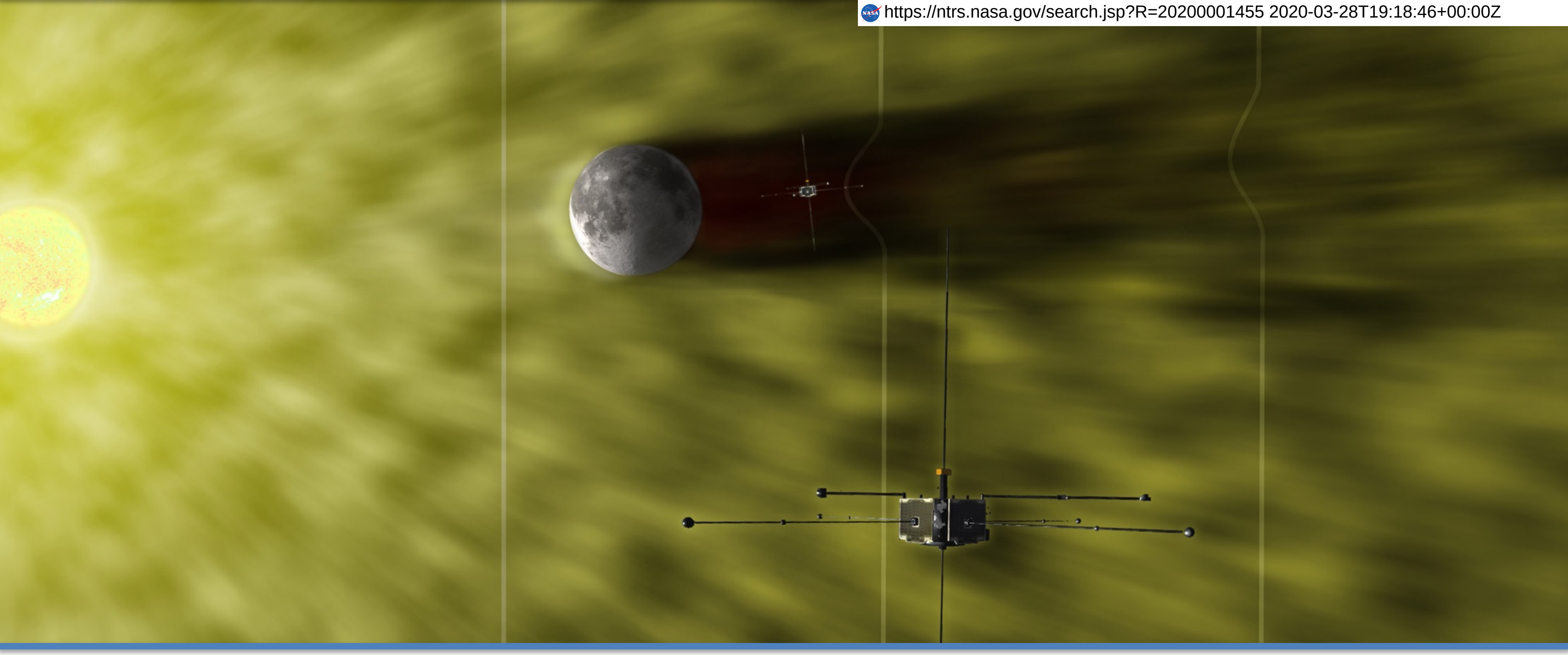

A multi model electromagnetic sounding investigation of the lunar interior

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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

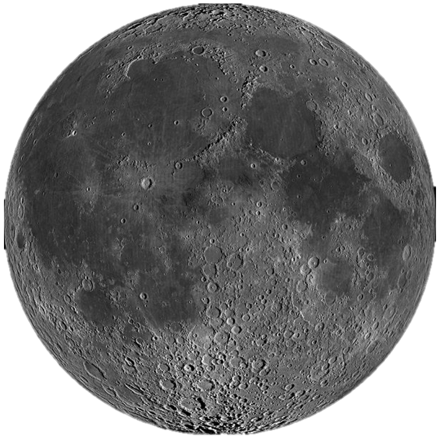
Fuqua Haviland, H., Poppe, A. R., Fatemi, S., Delory, G. T., & de Pater, I. (2019). Time-dependent hybrid plasma simulations of lunar electromagnetic induction in the solar wind. *Geophysical Research Letters*. doi.org/10.1029/2018GL080523

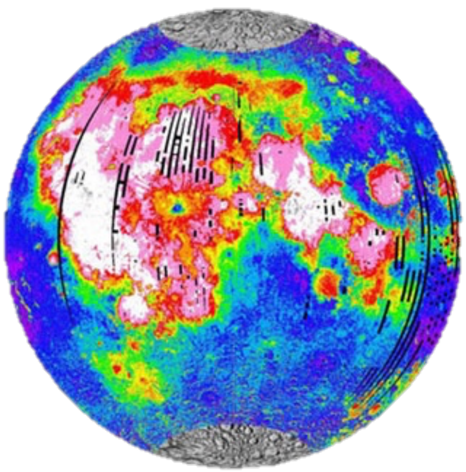
Fatemi, S., **Fuqua, H. A.**, Poppe, A. R., Delory, G. T., Halekas, J. S., Farrell, W. M., Holmström, M. (2015). On the confinement of lunar induced magnetic fields. Geophysical Research Letters, 42(17), 6931–6938. doi:10.1002/2015GL065576

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

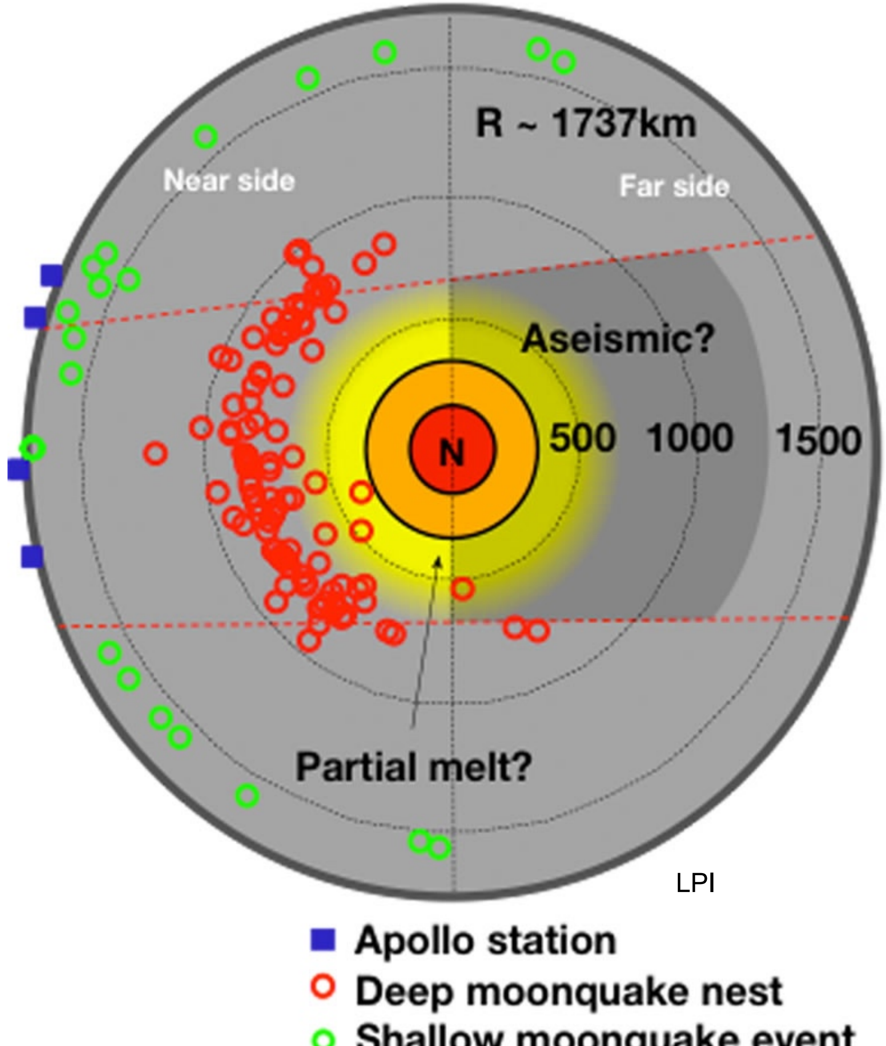
Driving Science Question

Near Side



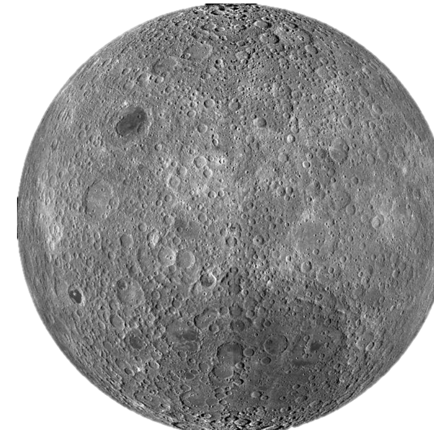


Equatorial Cross-section

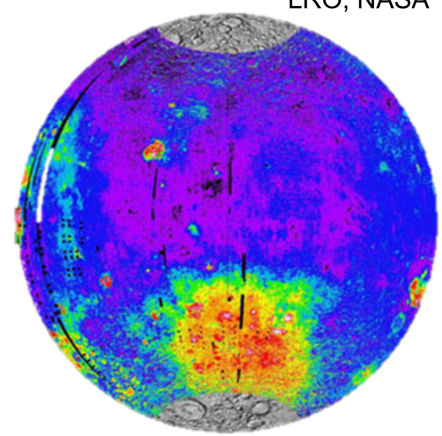


LPI

Far Side



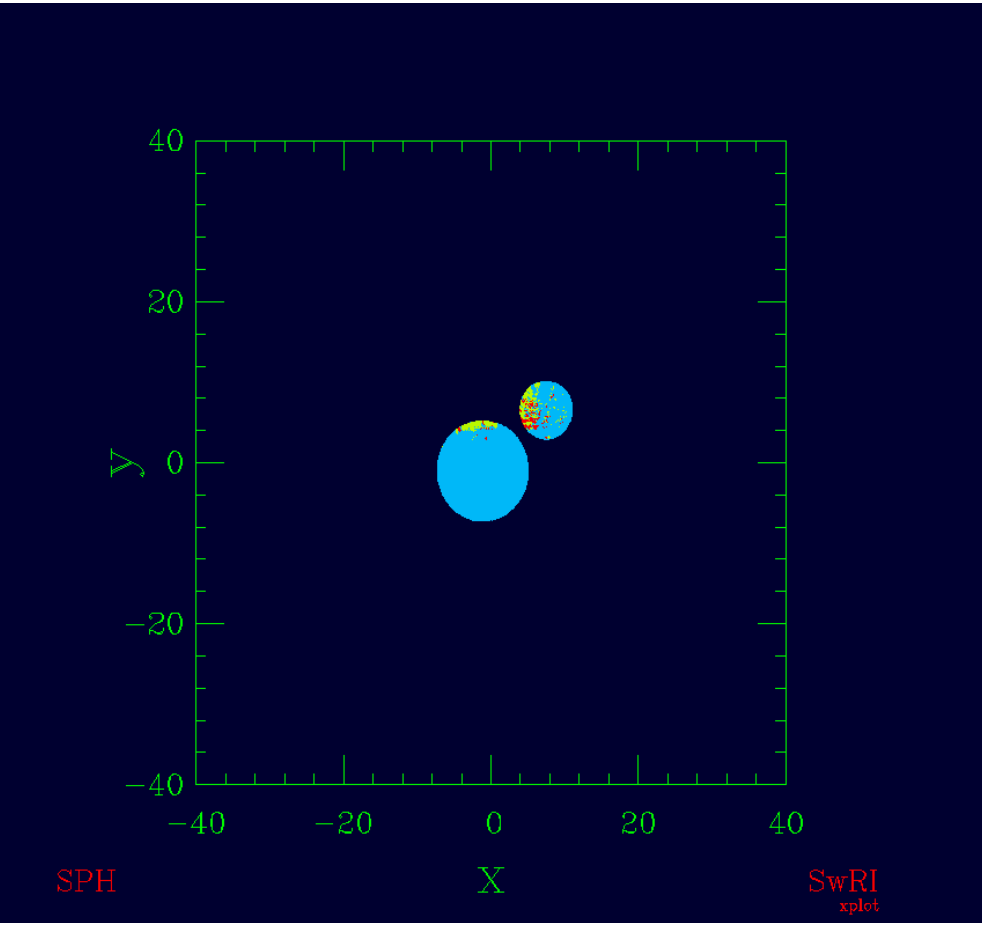
LRO, NASA



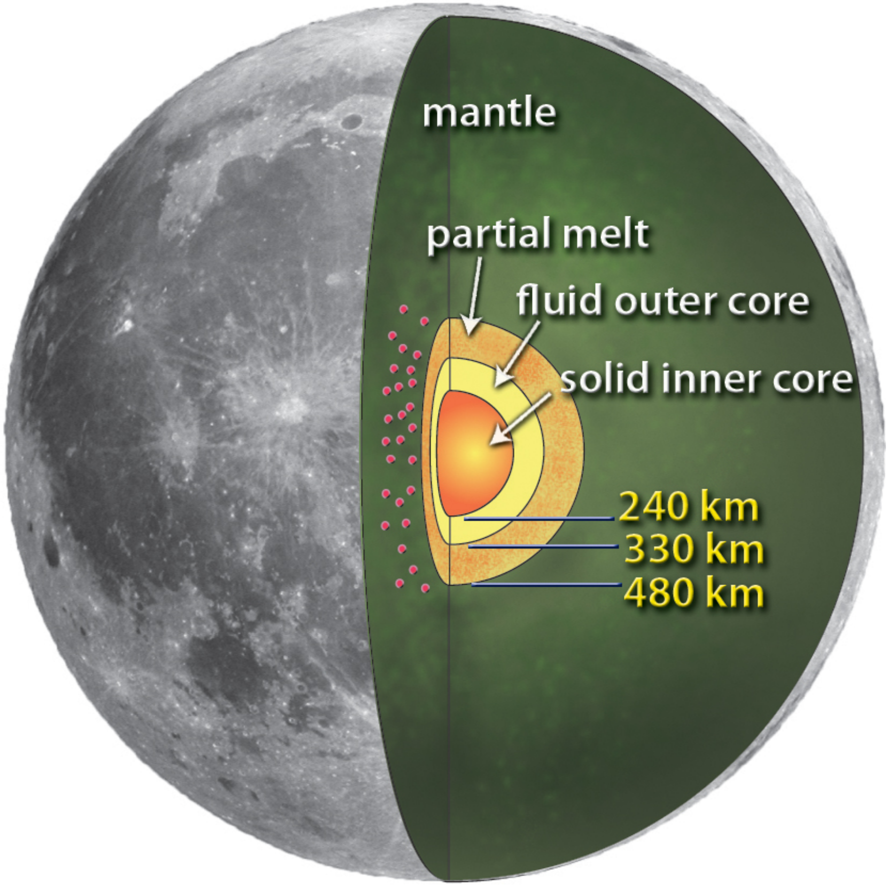
Hiesinger & Head, 2006

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

Lunar Origin Theories



Canup et al. 2016



Weber et al., 2011

The current state is key to constraining origin theories.

Magma Ocean Crystallization

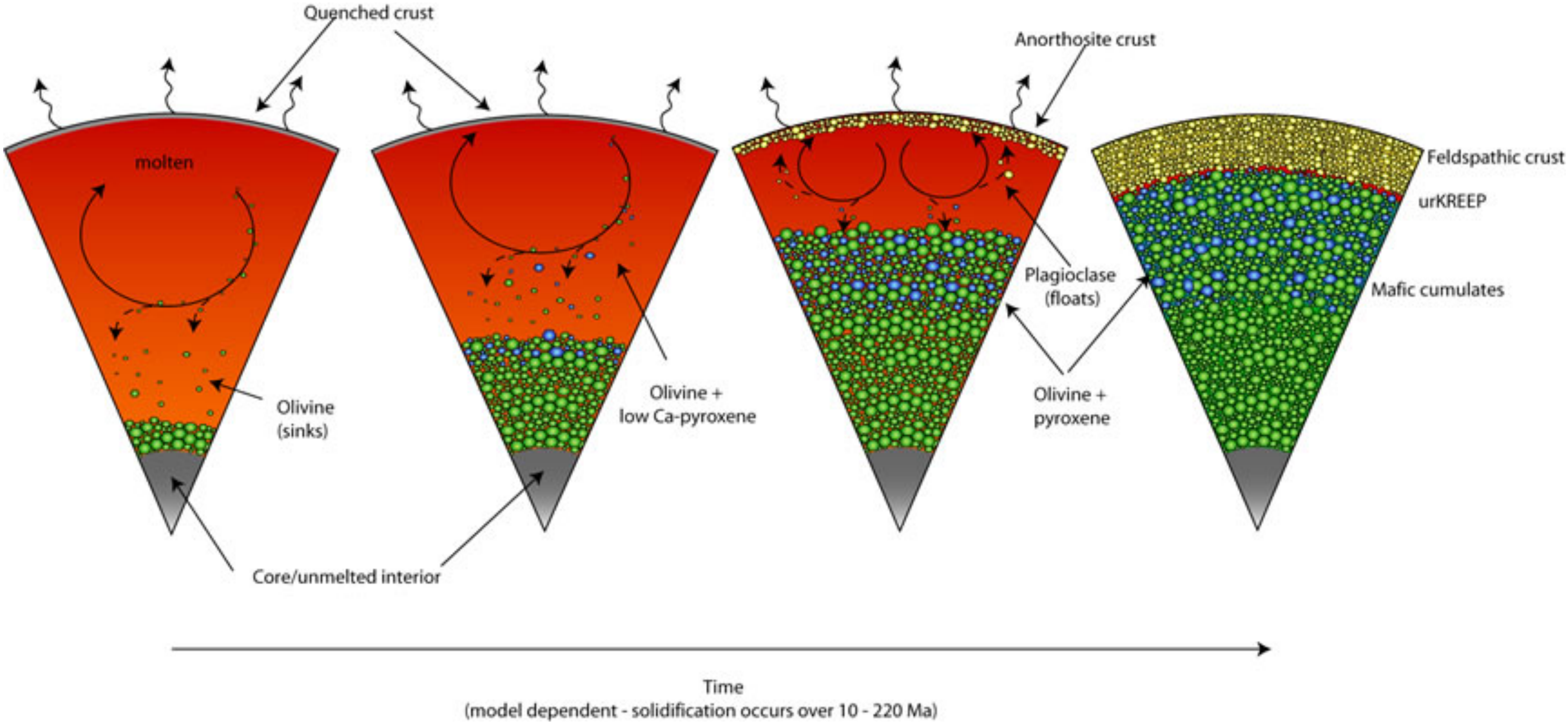
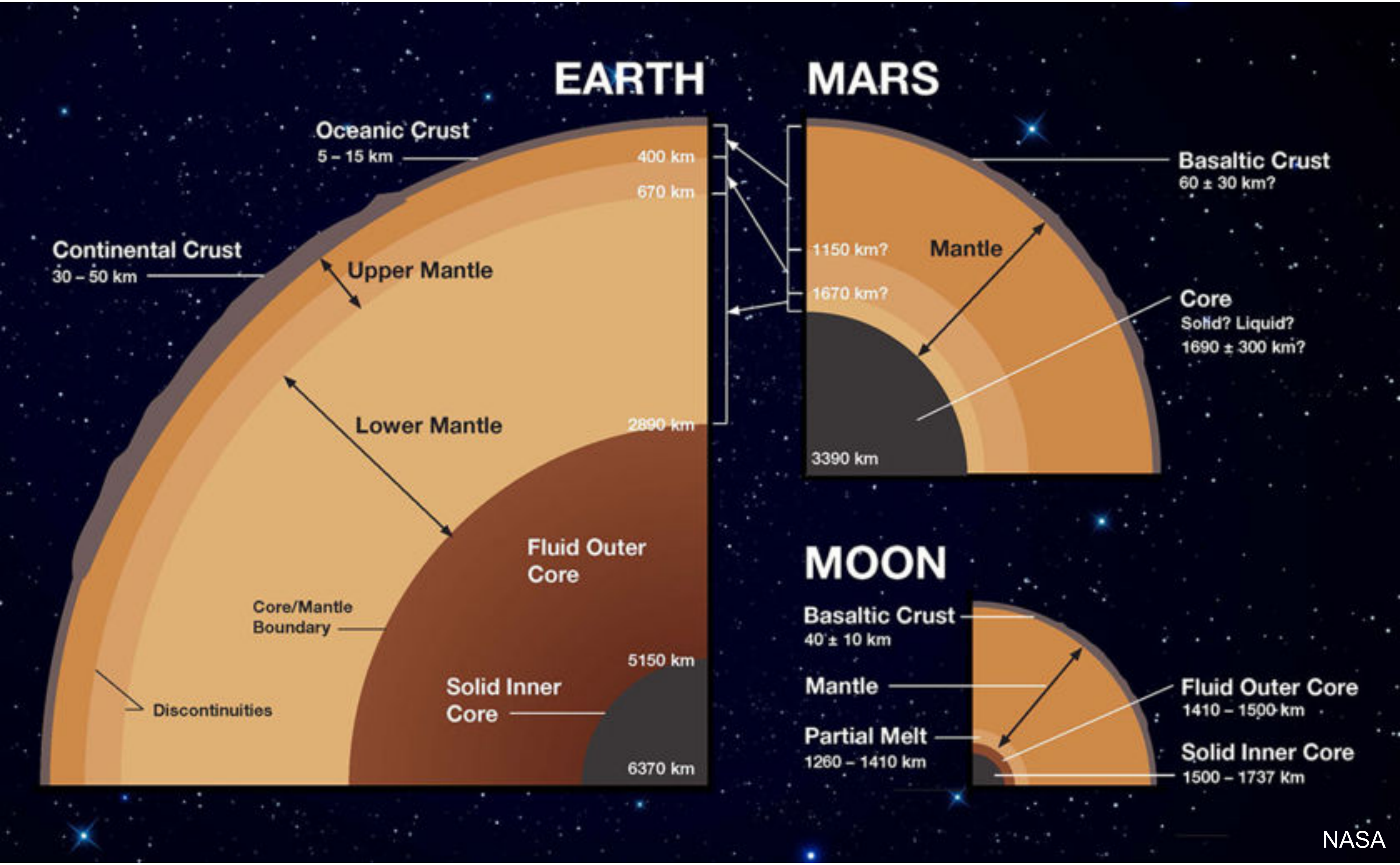


Image source: LPI

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

Terrestrial Planet 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 the induced fields interact with wake fields?

EM Sounding is a powerful tool capable of constraining the electrical conductivity of the Moon, and hence, temperature, core thickness, mantle, and crust/PKT structure at depth.

Earth-Sun-Moon Space Environment

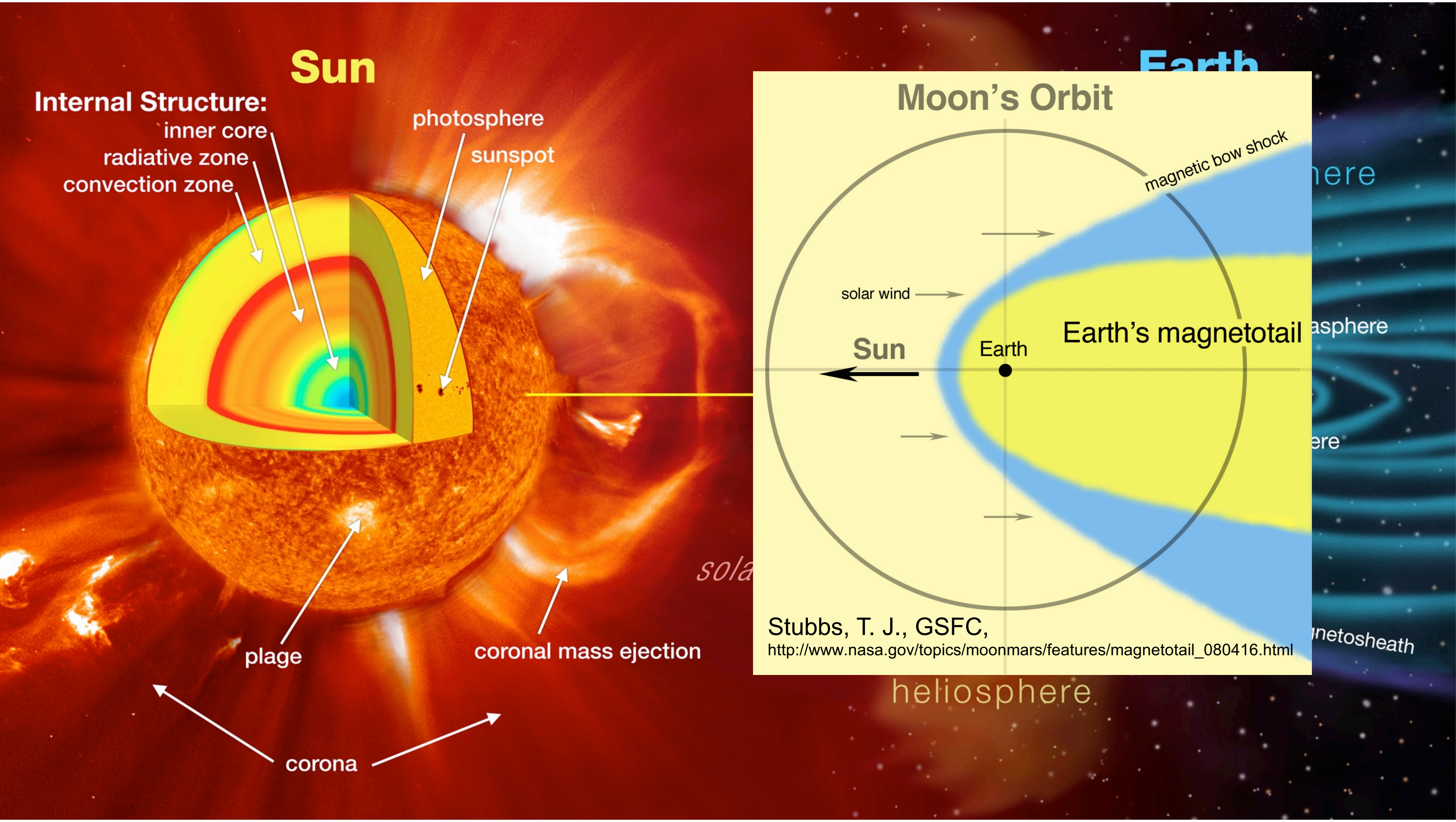
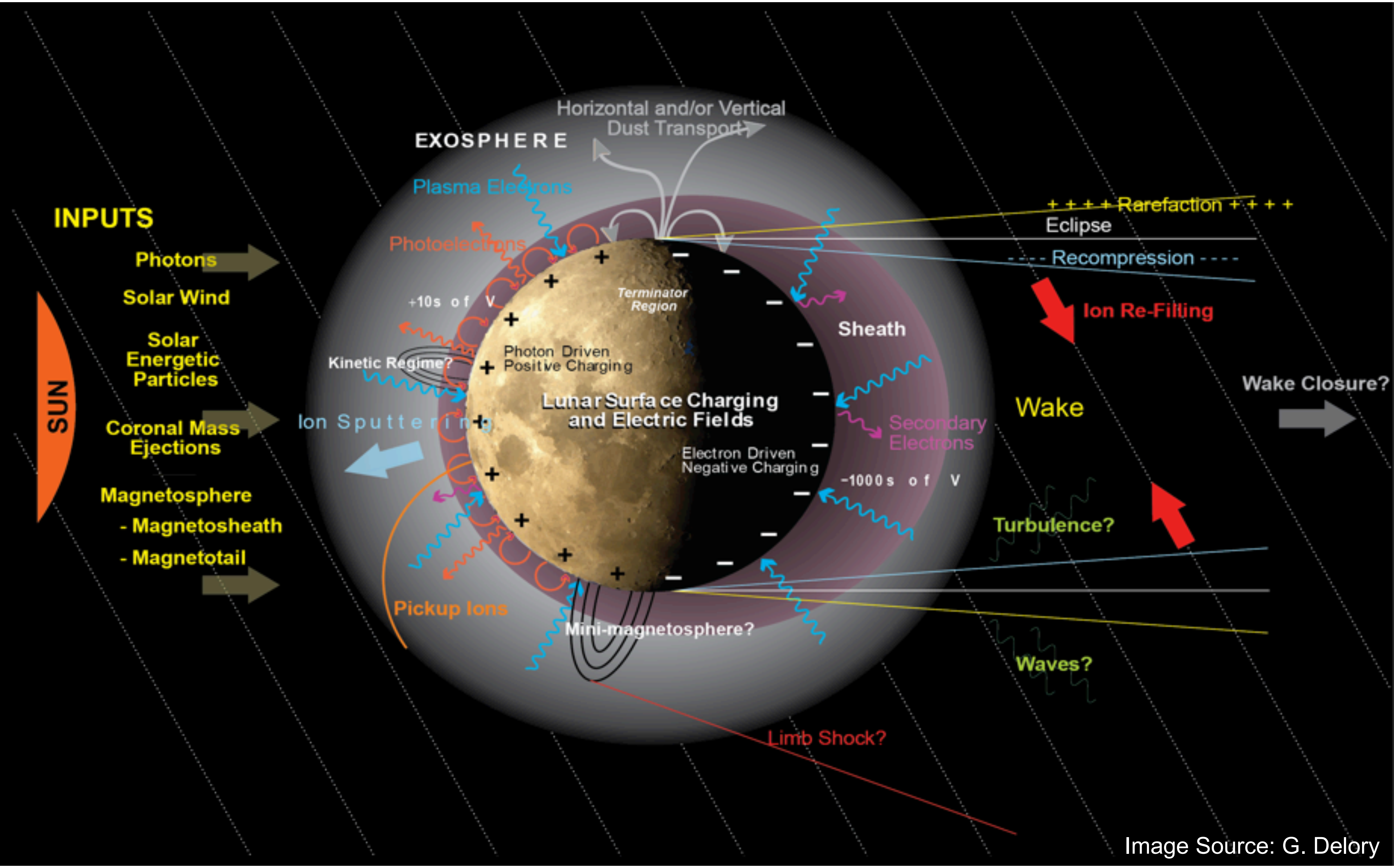
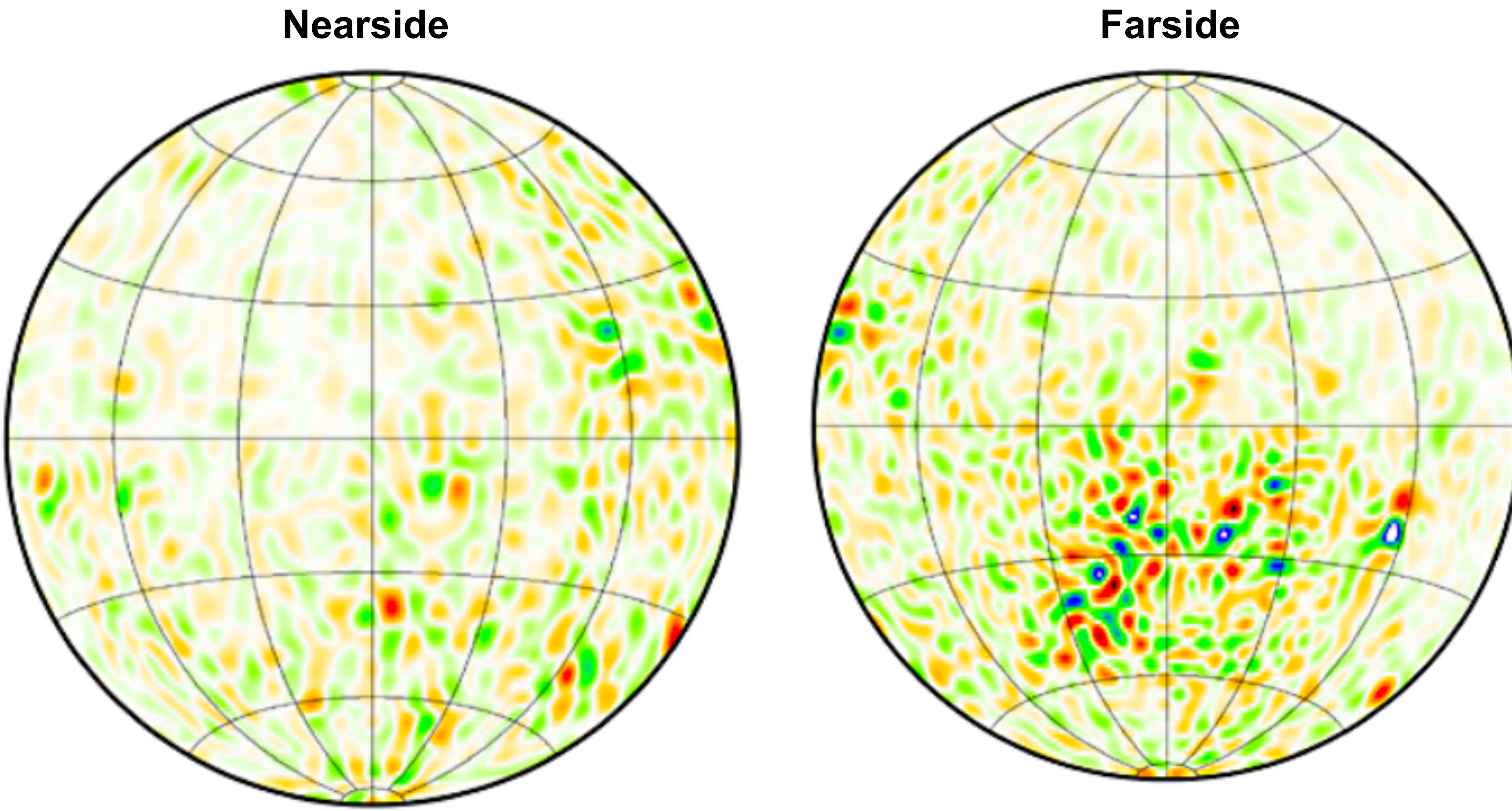


Image Source: NASA

Solar Wind Space Plasma Environment

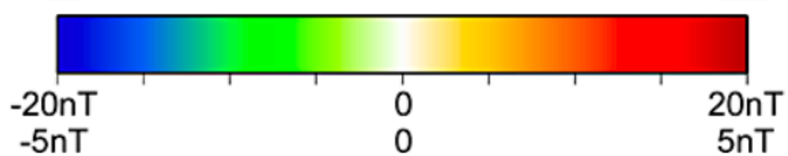


Lunar Crustal Magnetic Fields



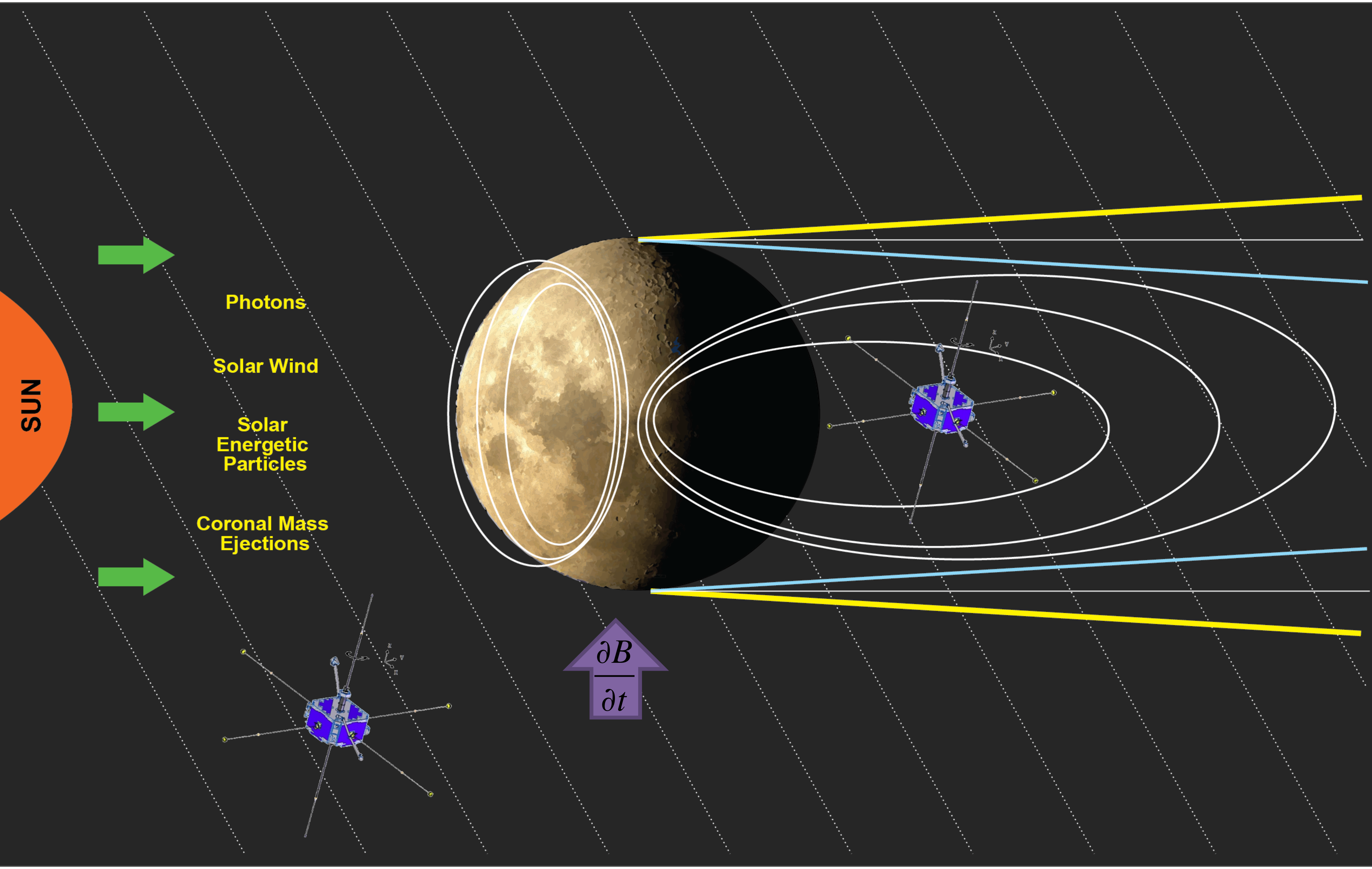
Regions of weak crustal fields are prevalent.

Equivalent surface Field Strength.



Tsunakawa et al., 2010

Asymmetric Plasma Confinement



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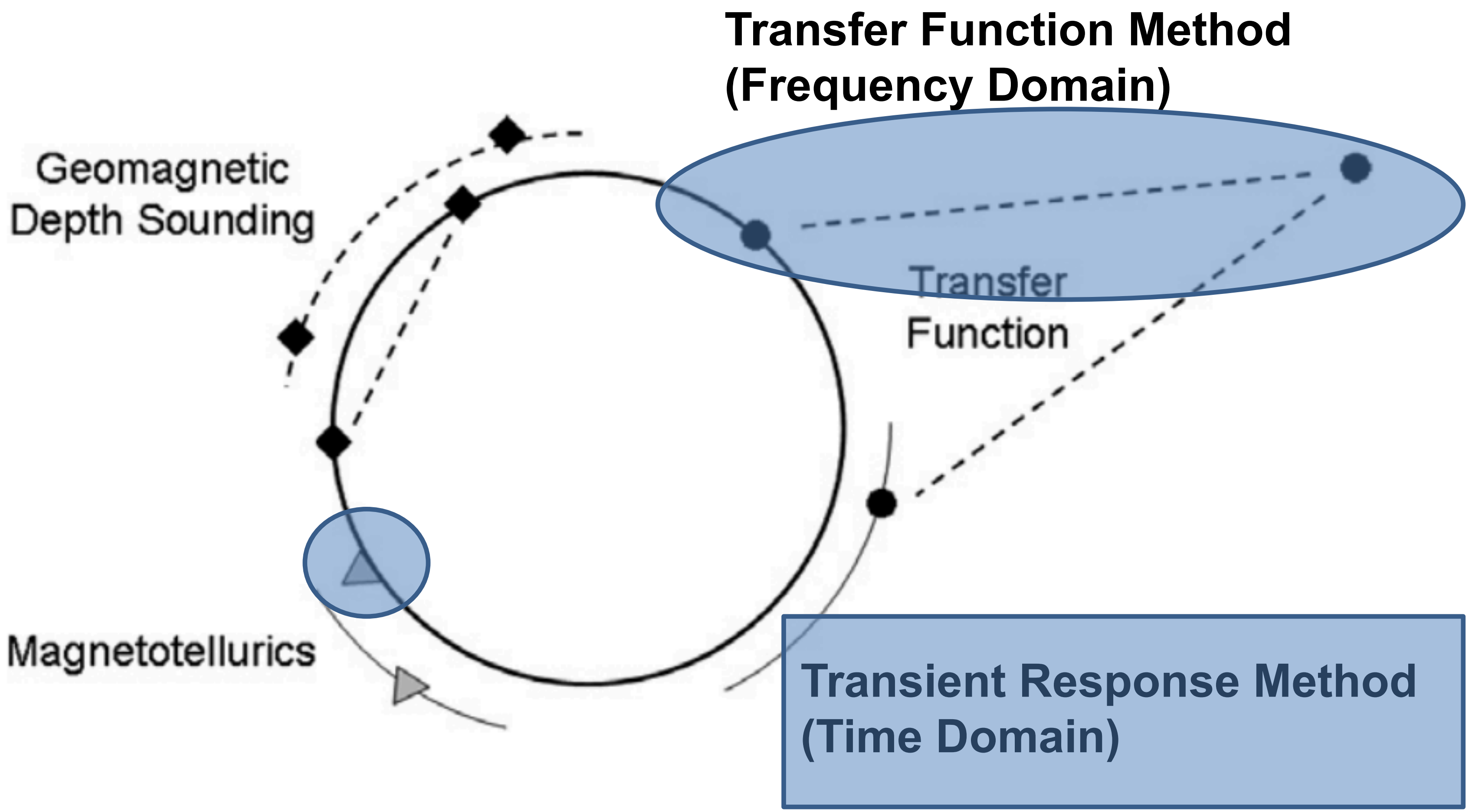
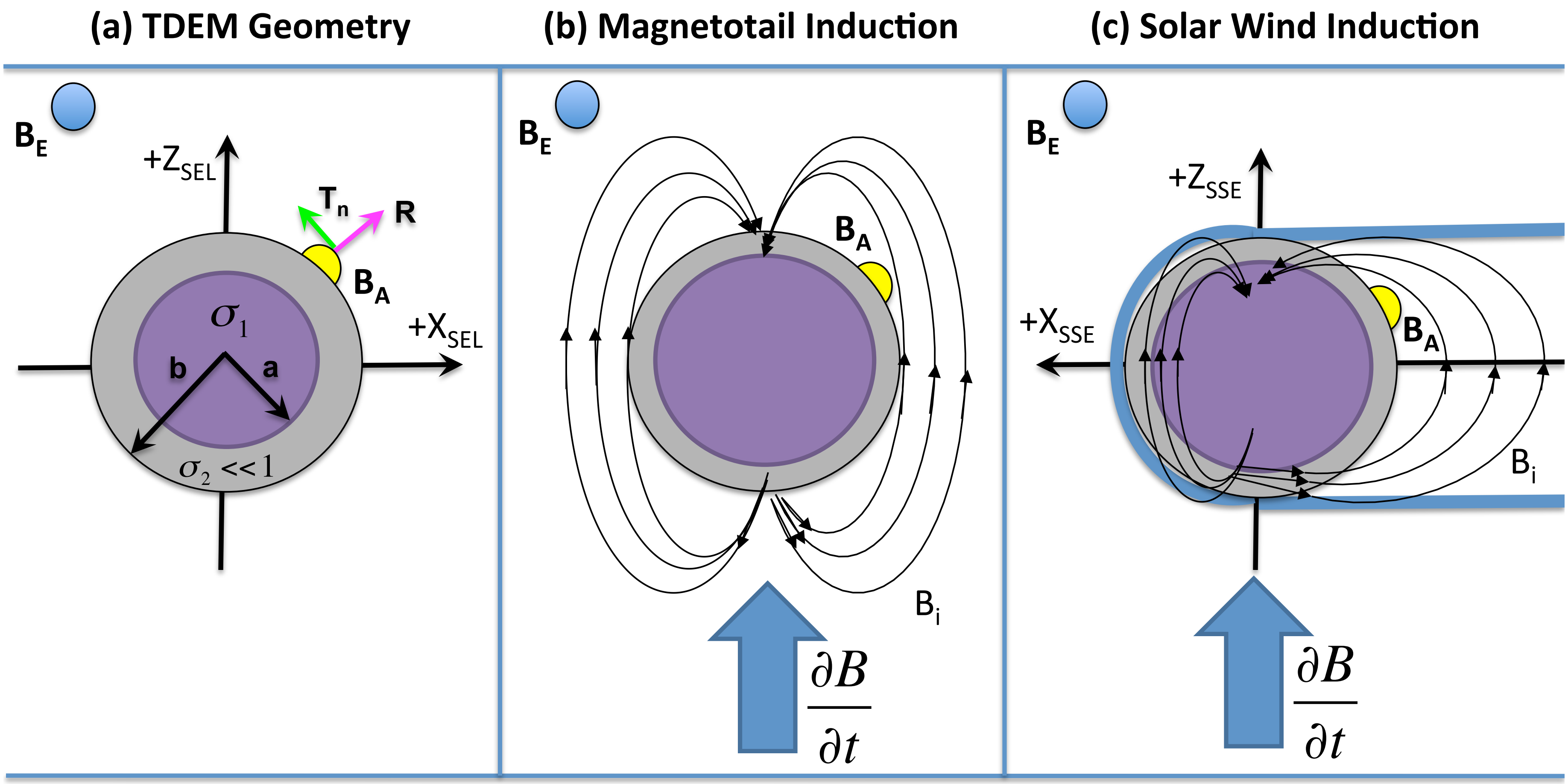
Planetary EM Geophysical Methods



Grimm and Delory, 2012

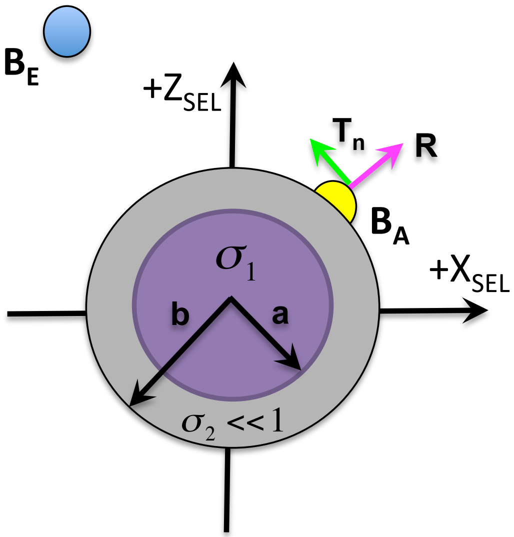
Lunar Electromagnetic (EM) Sounding Transient Response Method



Fuqua Haviland et al., 2019

The Apollo Picture

Time Domain EM (TDEM) Sounding Vacuum Model

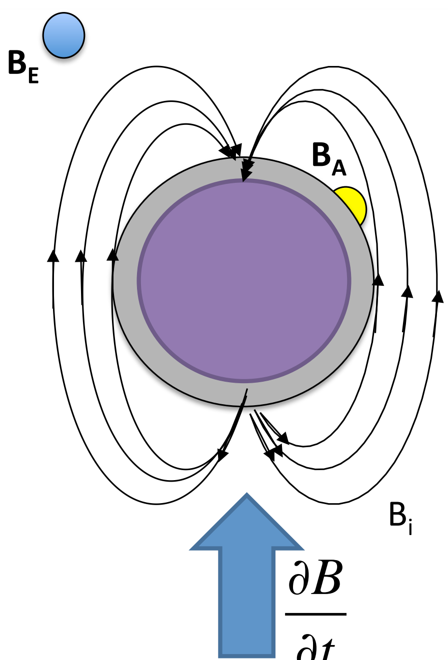


$$B_{A,R}(t) \propto -\left(\frac{a}{b}\right)^3 \Delta B_{E,R} F(t)$$

$$B_{A,T}(t) \propto \left(\frac{a}{b}\right)^3 \Delta B_{E,T} F(t)$$

$$F(t) \propto \exp\left(-t / \sigma_a a^2\right)$$

Dyal & Parkin, 1971



Fuqua Haviland et al., 2019

TDEM Sounding Vacuum Model

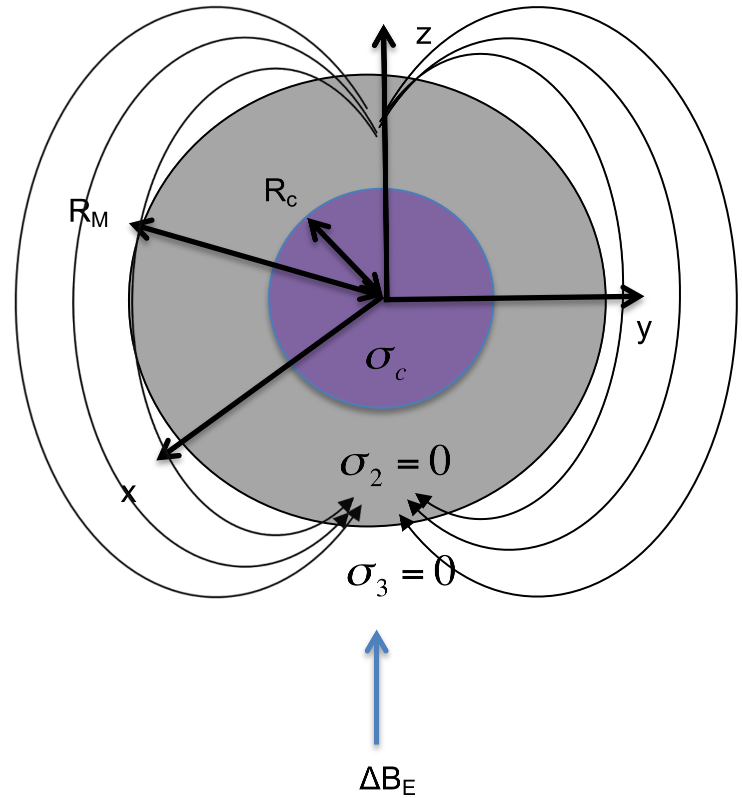
Dyal & Parkin, 1971:

$$B_{Ax}(t) = -3\left(\frac{R_c}{R_M}\right)^3 \Delta B_{Ex} F(t) + B_{Exf}$$

$$B_{Ay}(t) = \frac{3}{2}\left(\frac{R_c}{R_M}\right)^3 \Delta B_{Ey} F(t) + B_{Eyf}$$

$$B_{Az}(t) = \frac{3}{2}\left(\frac{R_c}{R_M}\right)^3 \Delta B_{Ey} F(t) + B_{Ezf}$$

$$F(t) = 2\pi^{-1/2} x \sum_{s=1}^{\infty} \frac{1}{s^2} \exp\left(-s^2\pi^2 t / \sigma_c \mu_o R^2\right)$$



$$A_0 = A_{1=core}$$

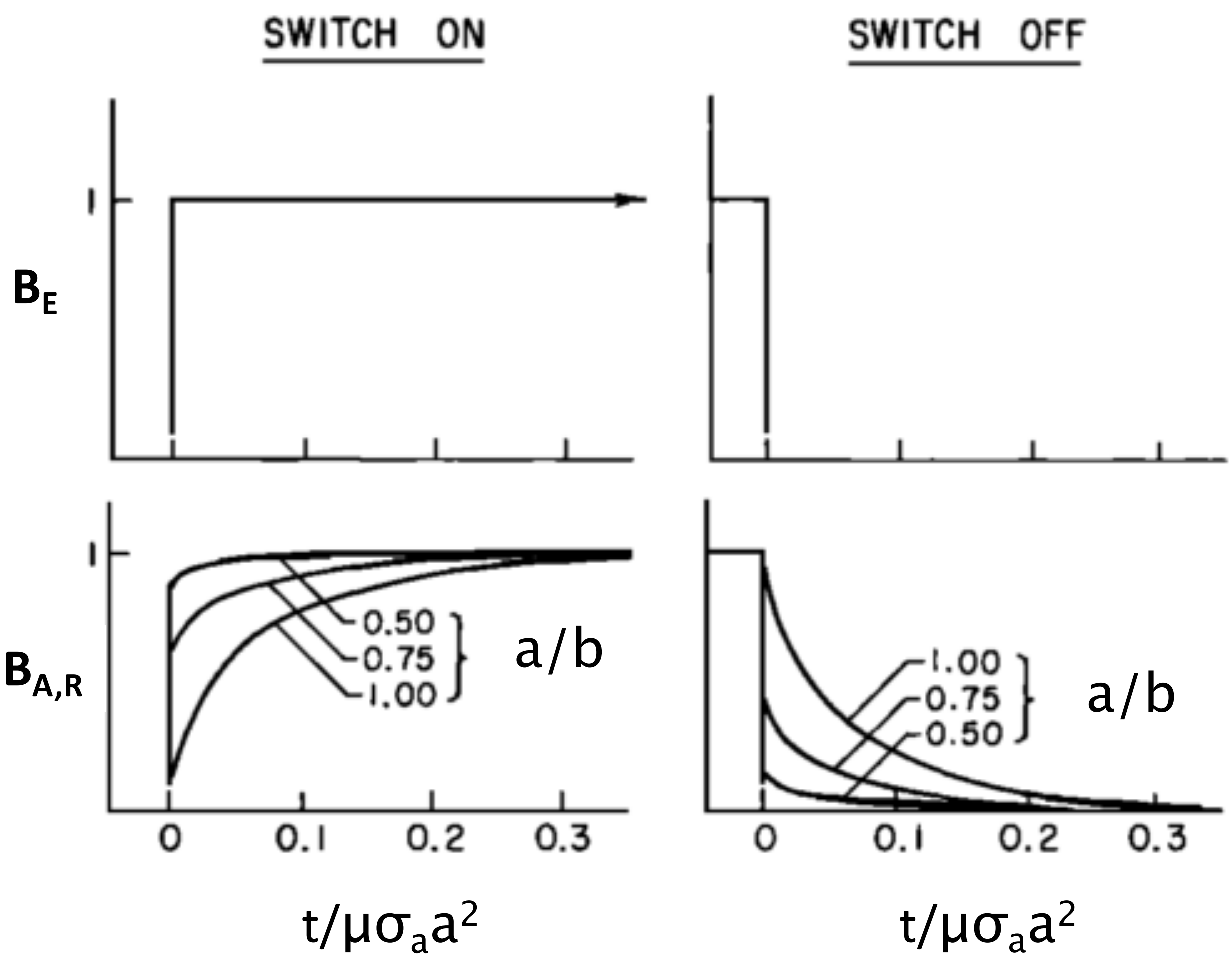
$$\mu_o \frac{\partial}{\partial r}(rA_0) = \mu_o \frac{\partial}{\partial r}(rA_{1=core})$$

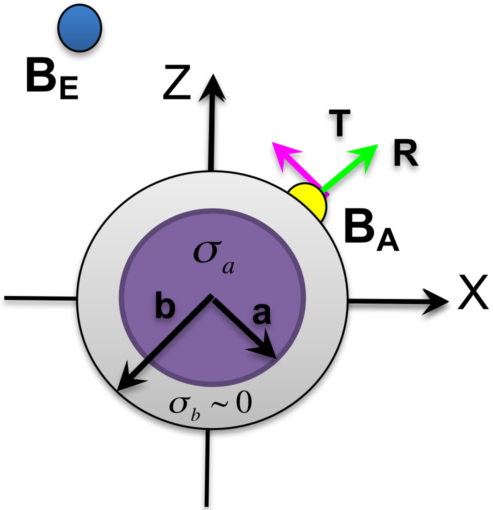
$$B_{\perp 0} = B_{\perp 1}$$

B_A = Total Field, measured near surface (Wake Probe)

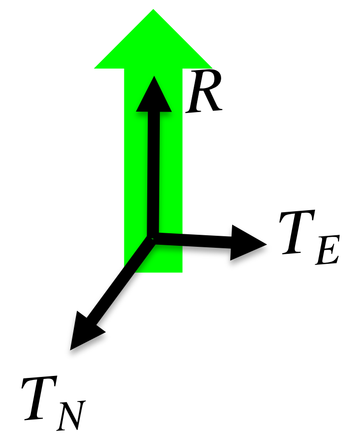
B_E = External Driving Field (Reference Probe)

TDEM Sounding Theory



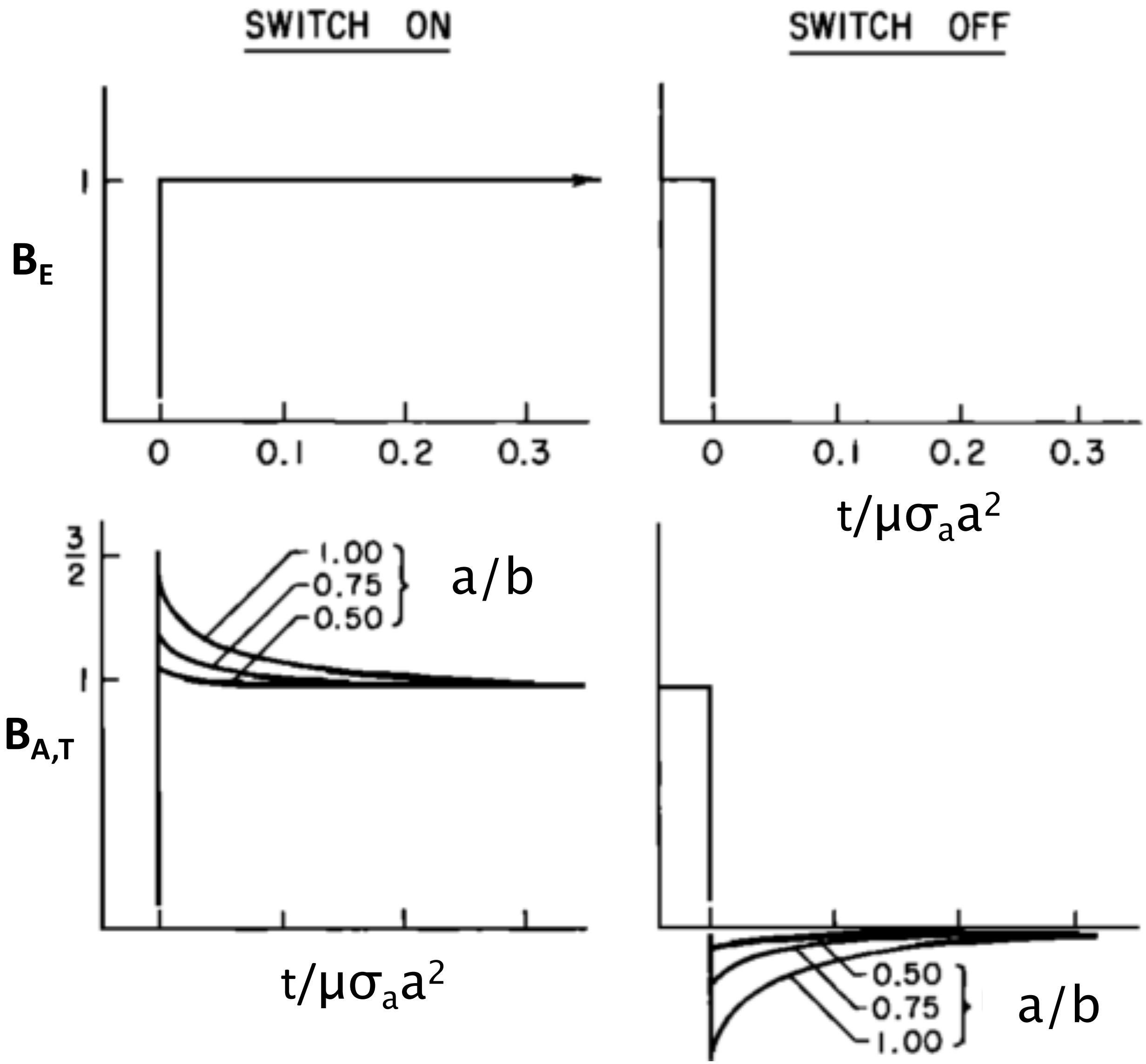


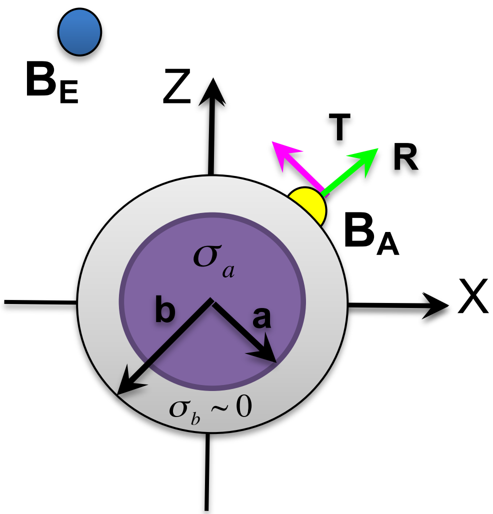
Fuqua Haviland et al., 2019



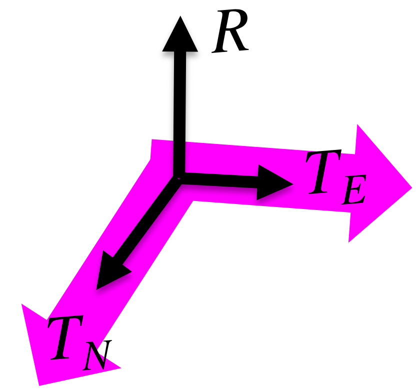
Dyal & Parkin 1971
Sonett, 1982

TDEM Sounding Theory





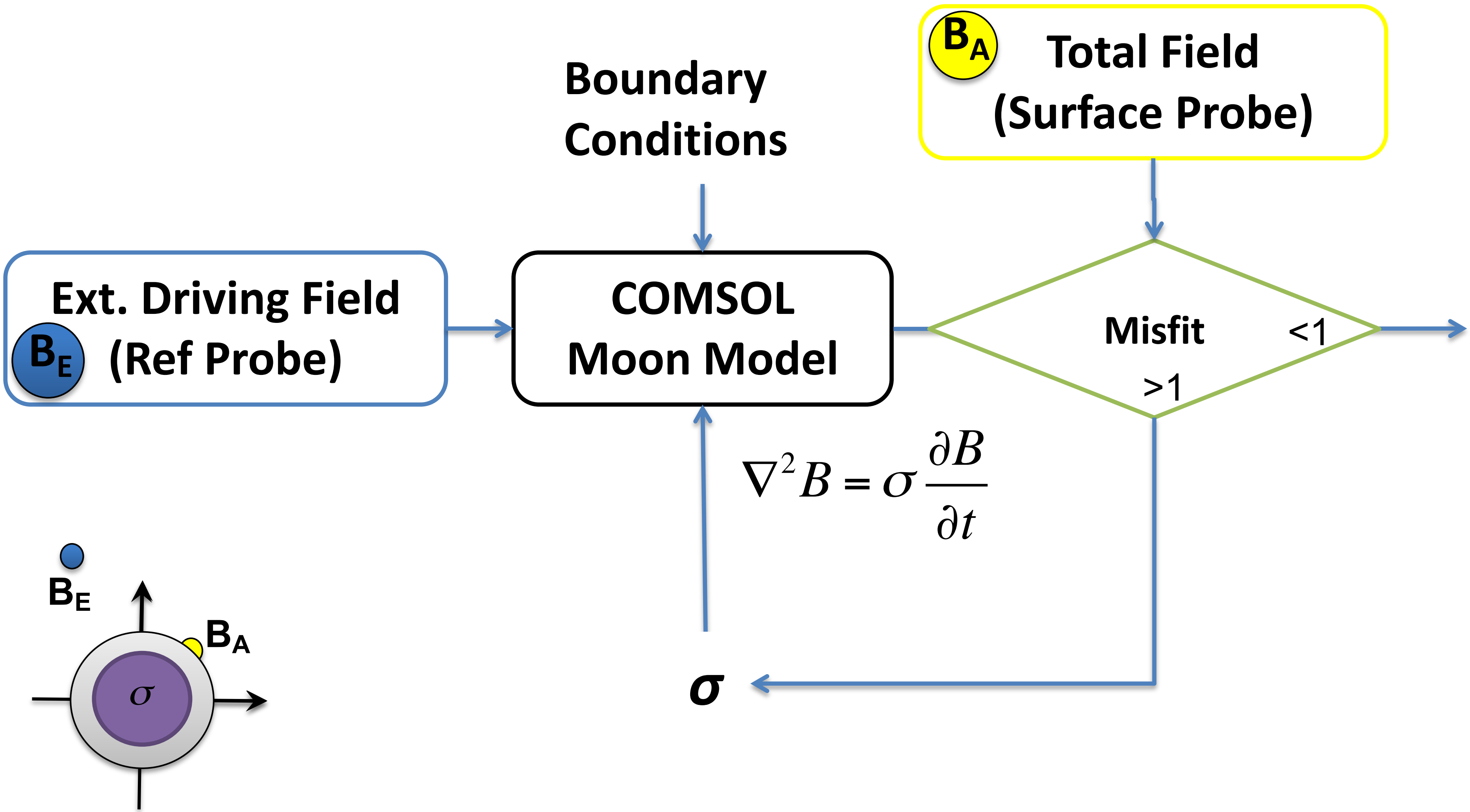
Fuqua Haviland et al., 2019



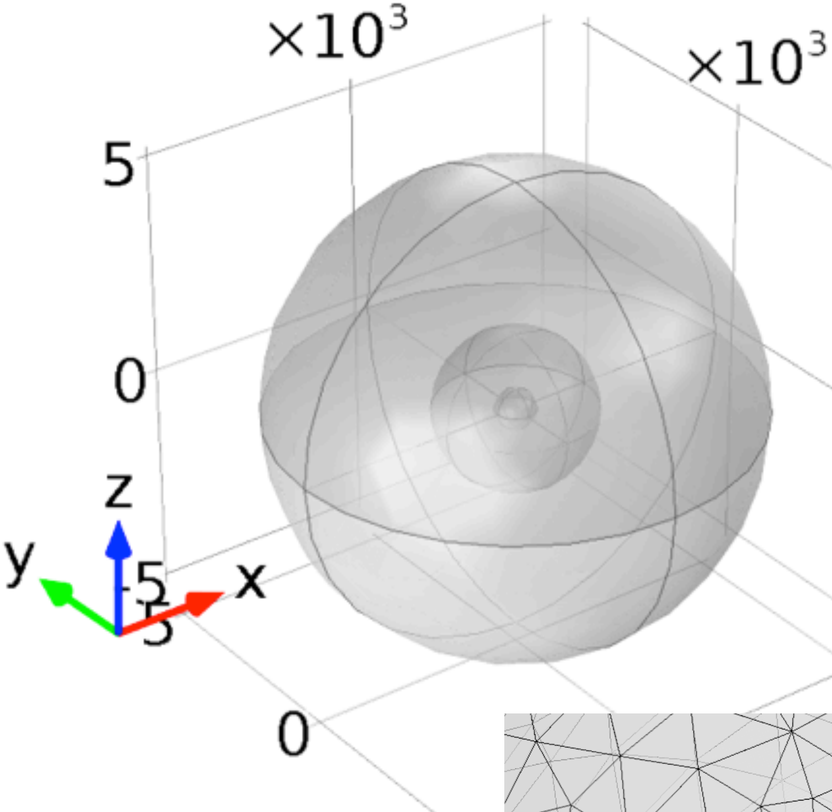
Dyal & Parkin 1971

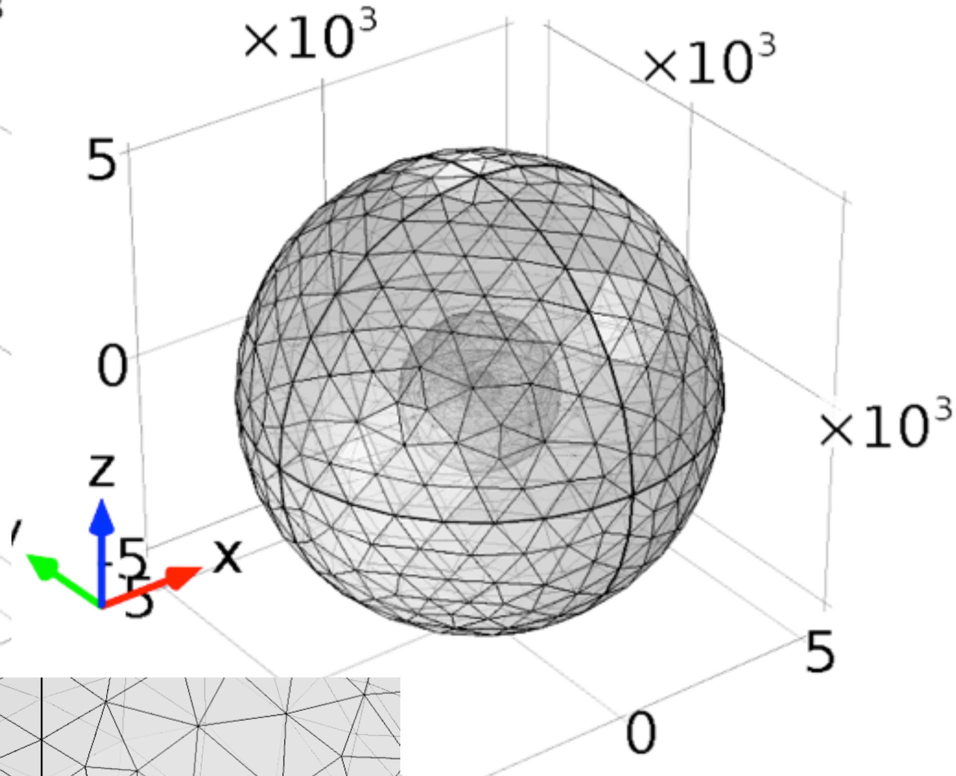
Sonett, 1982

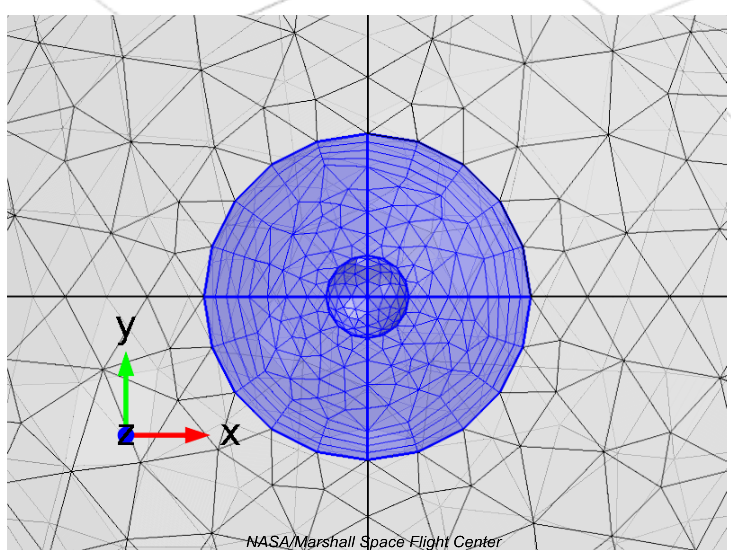
COMSOL Finite Element Method (FEM) Implementation



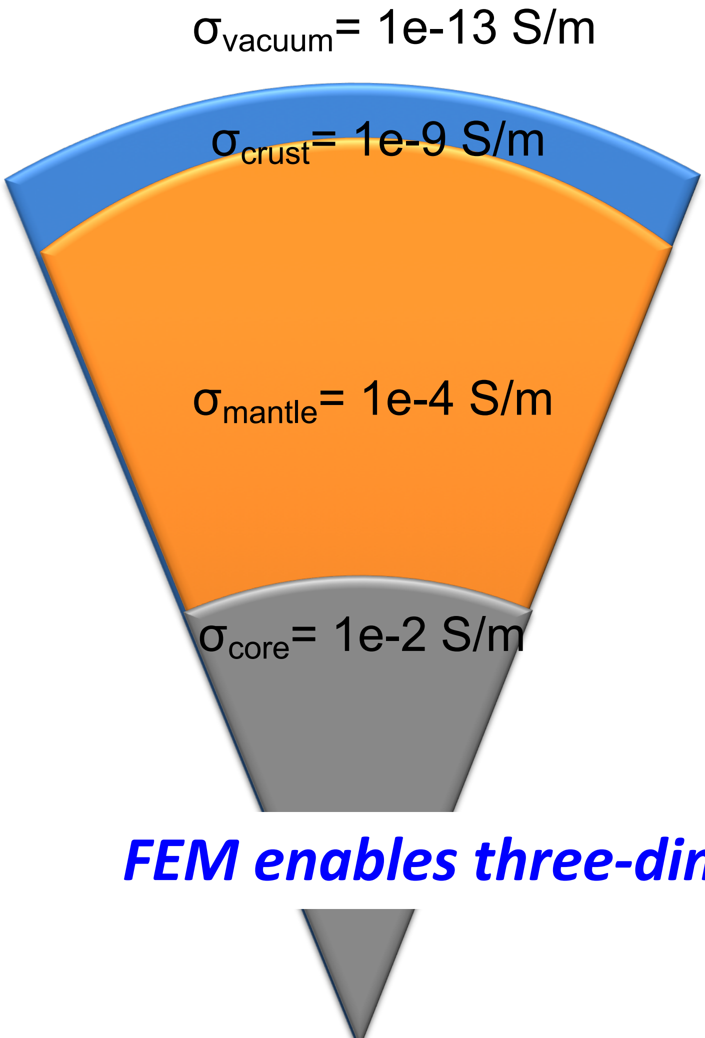
COMSOL FEM Forward Model

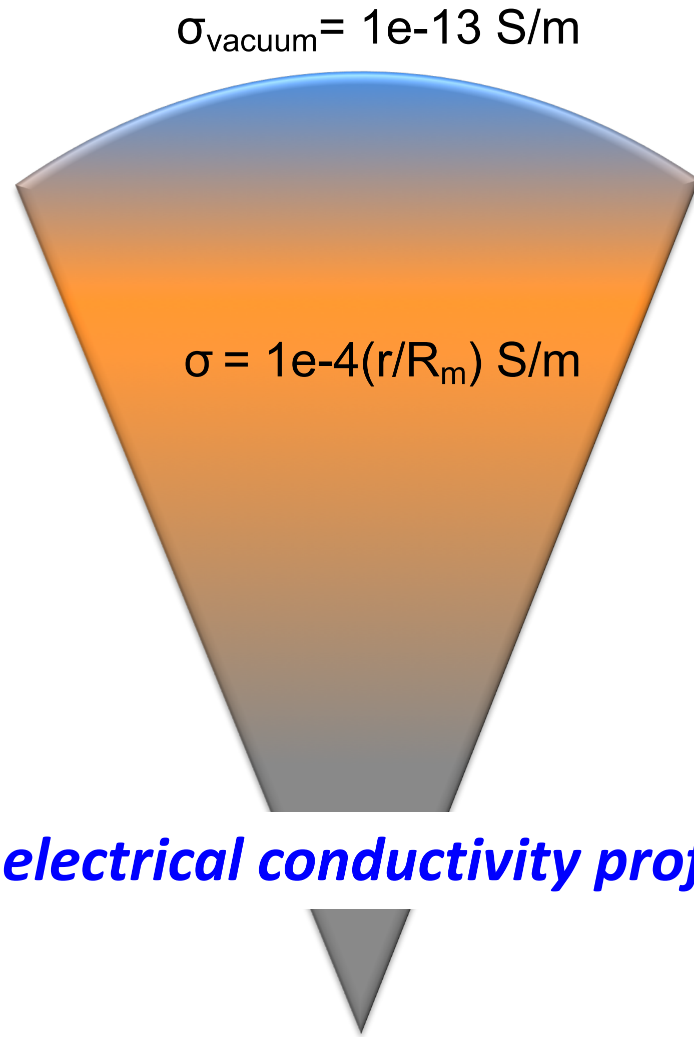






3D Electrical Conductivity Models

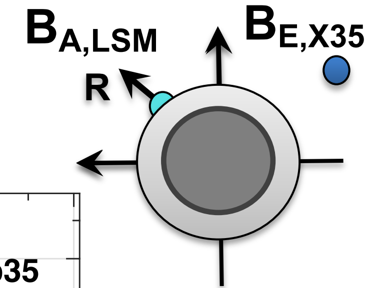


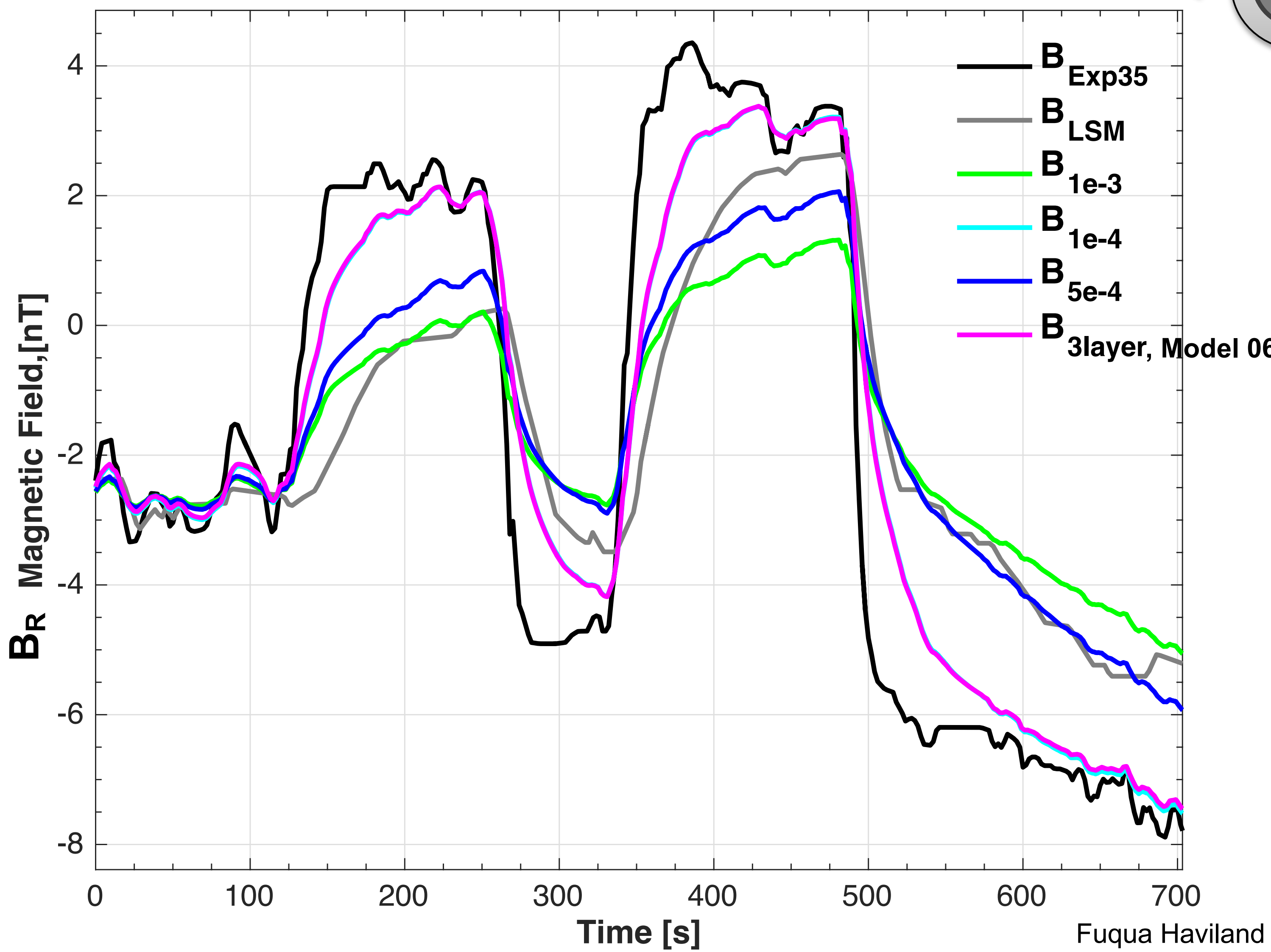


FEM enables three-dimensional electrical conductivity profiles.

Model 1: 3 Layer Model **Model 2: Radial Conductivity Profile (w/&w/o crust)**

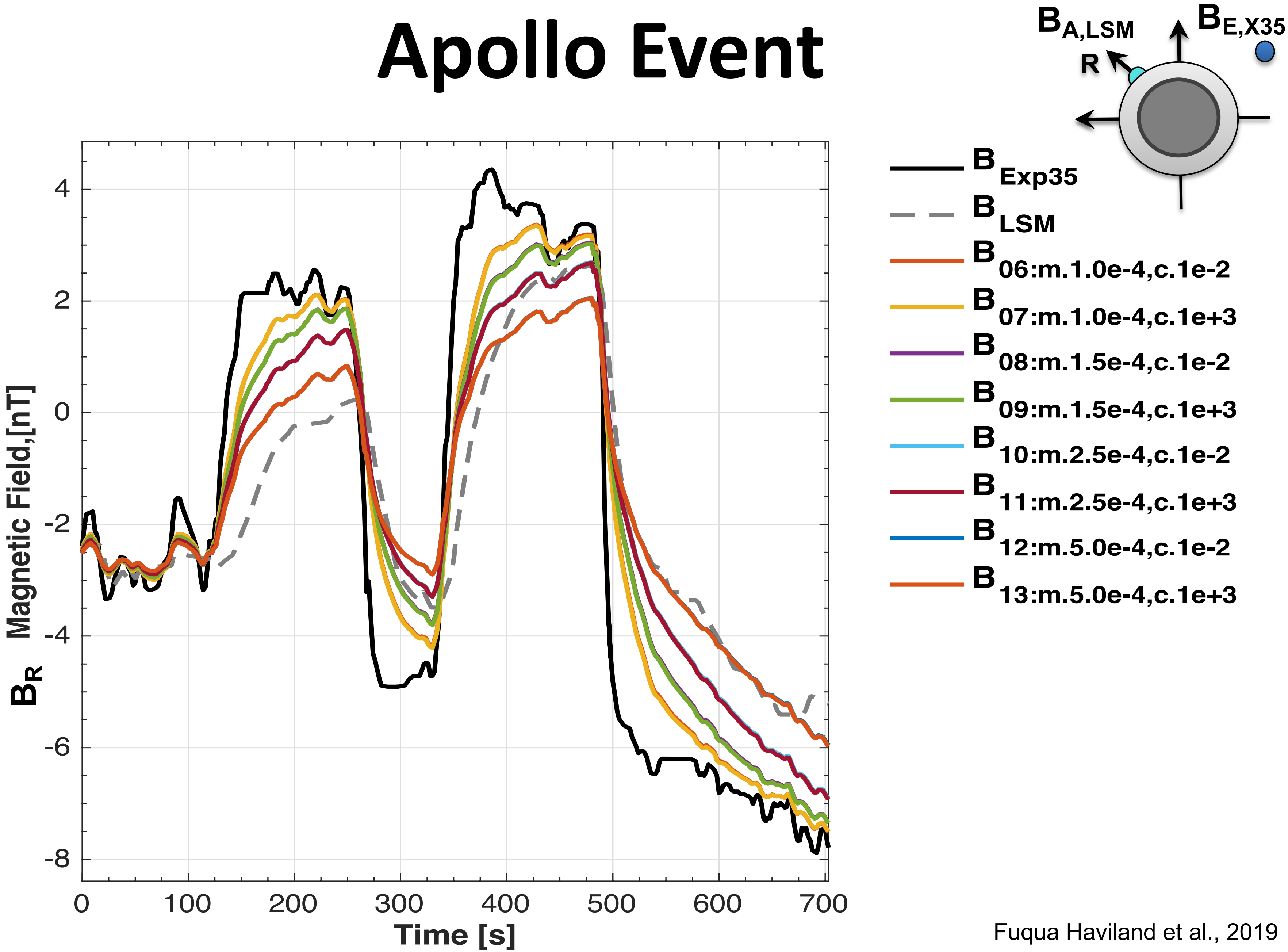
Apollo Event





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

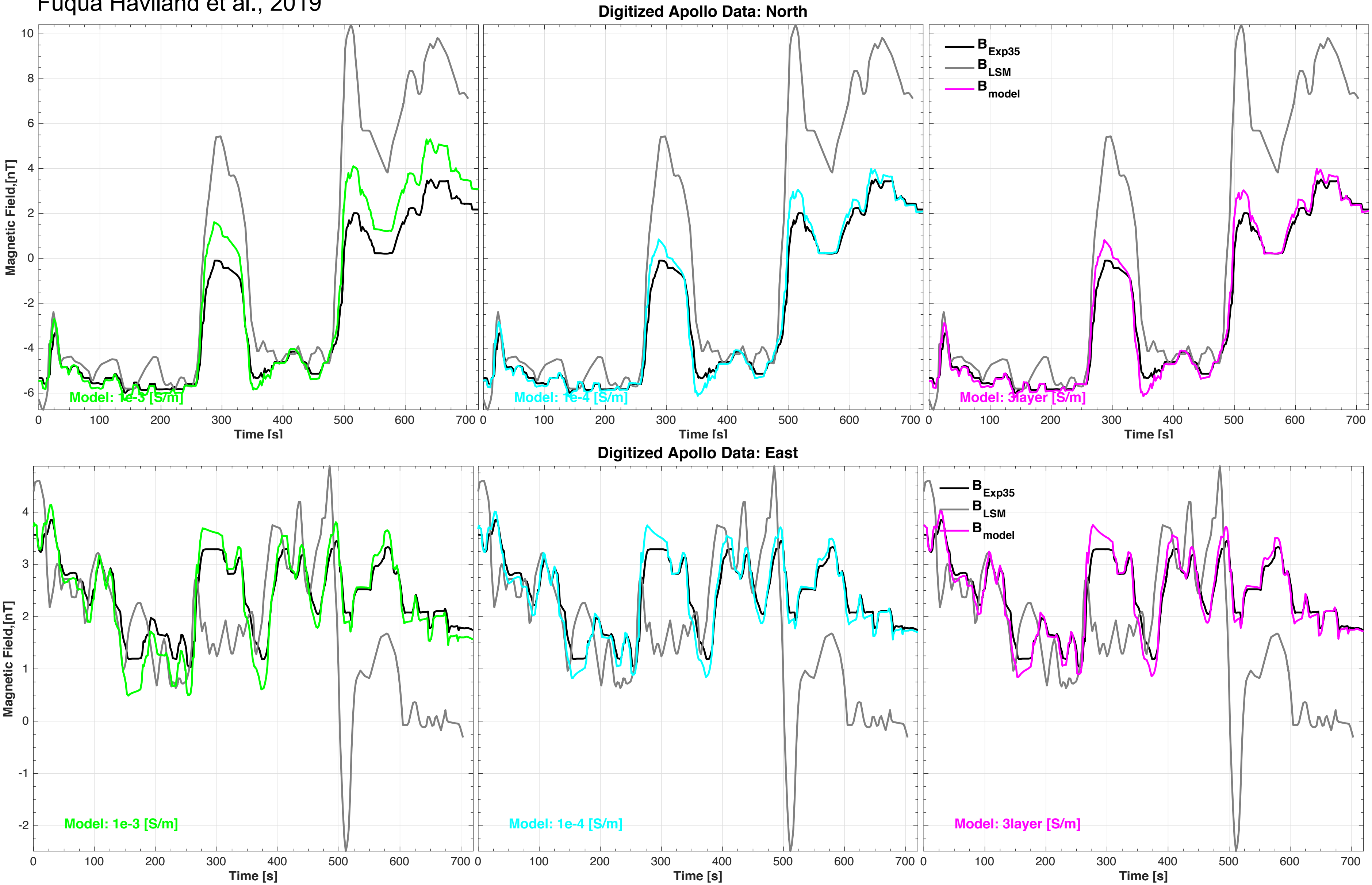
Apollo Event



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

Apollo Event

Fuqua Haviland et al., 2019



Challenges for TDEM

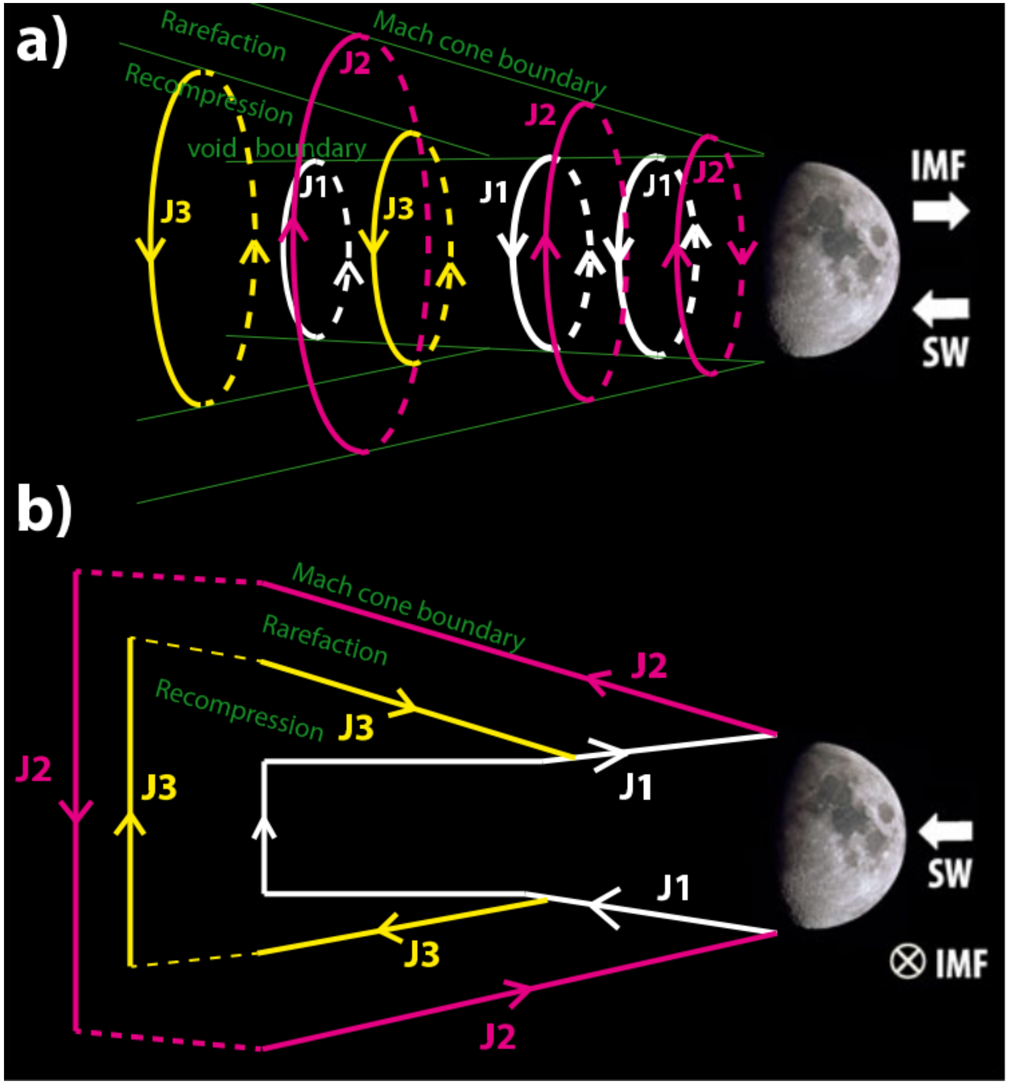
- Cannot fully capture all features of the Apollo surface observation with simple forward model.
  - Inversion?
- Does not consistently observe both the radial damping and tangential overshoot predicted by vacuum TDEM analytic theory.

How do induced magnetic fields interact with ambient plasma? Is wake confinement accurate? When can the vacuum approximation be applied?

(a) Plasma hybrid model with static magnetic dipole study

(b) Transient Plasma induction model

Wake Current Systems



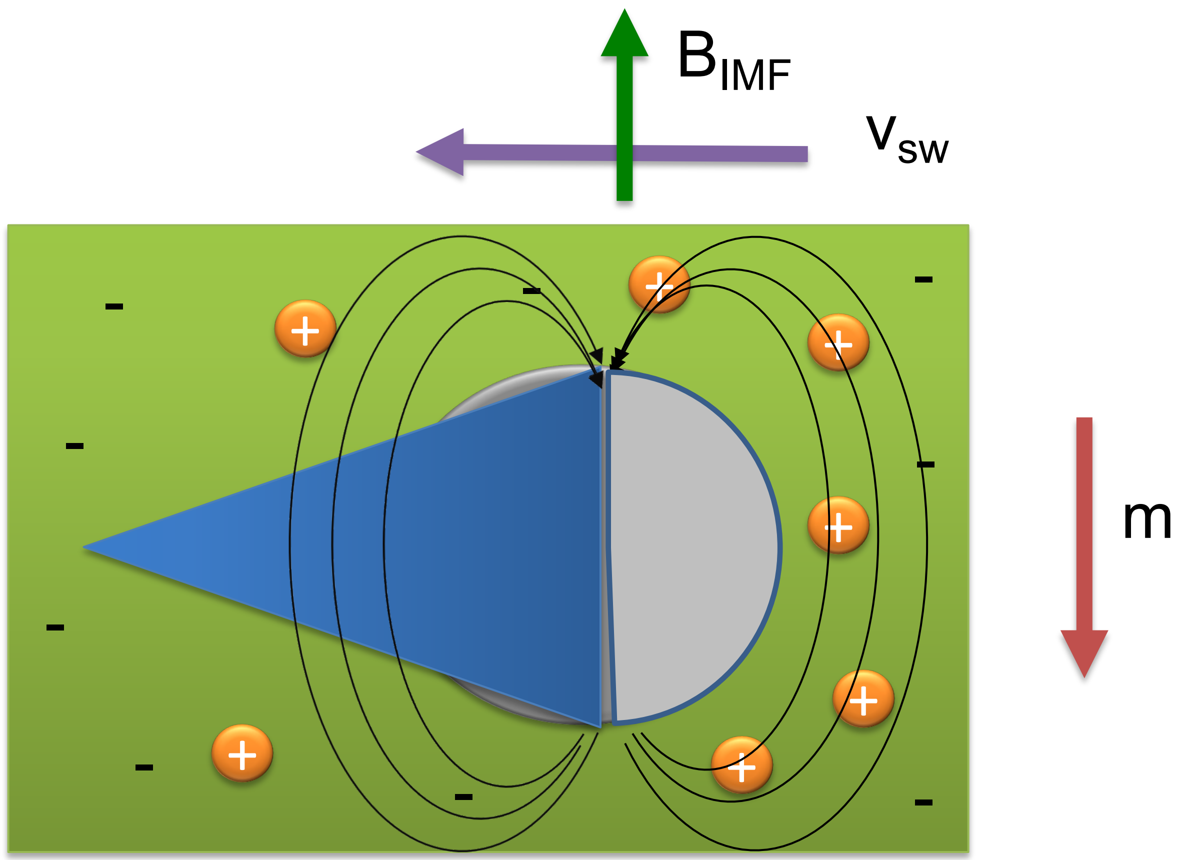
what we know:

- *wake forms on nightside due to dayside absorption and vacuum cavity*
- *wake current systems (incl. structure, extent) organize according to solar wind characteristics*

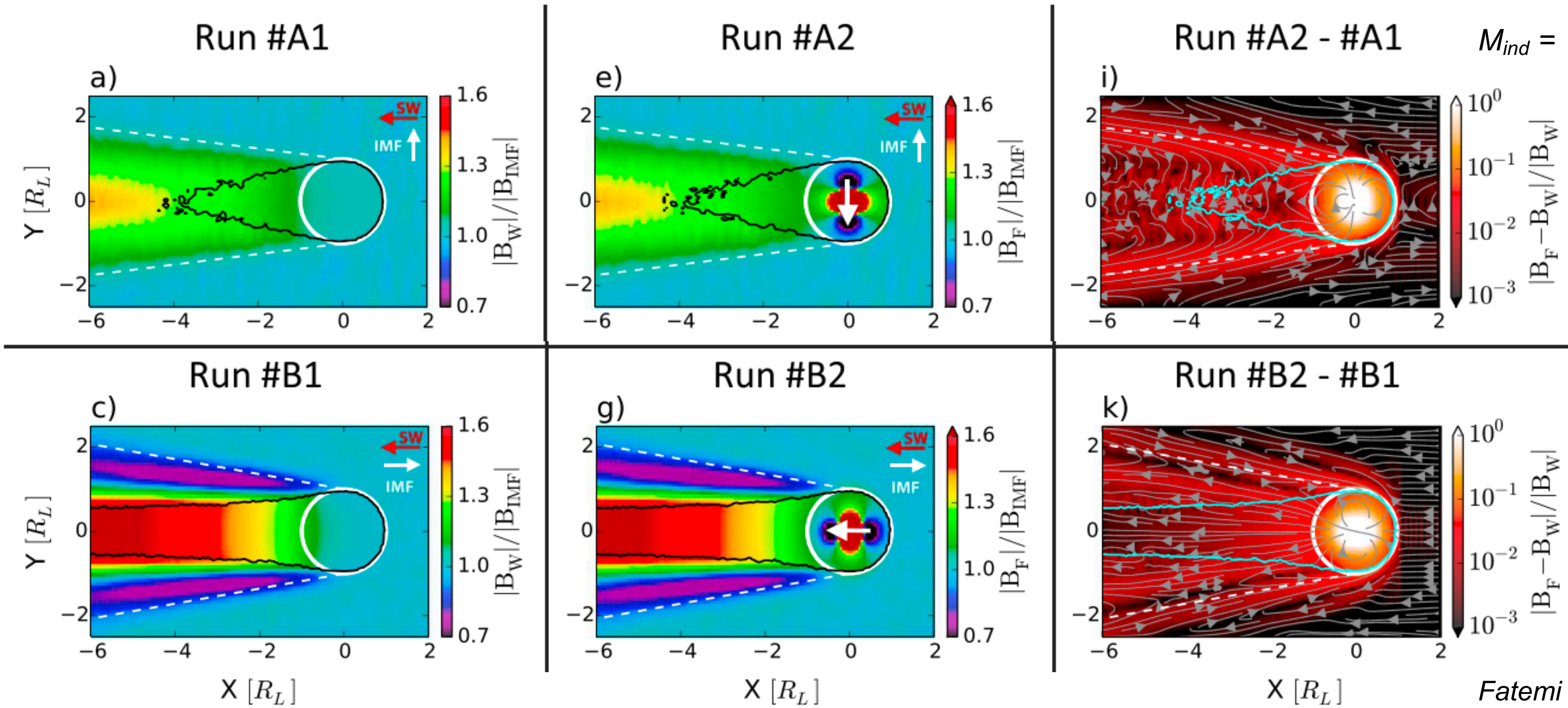
$\boldsymbol{v}_{sw}, \boldsymbol{B}_{IMF}$
n_e, n_i
T_e, T_i
$\sigma(r)$,t *This study*

Fatemi et al., [2014]
Holmstrom et al., [2012]

Static Plasma Hybrid Kinetic Model



Static Hybrid Model Results



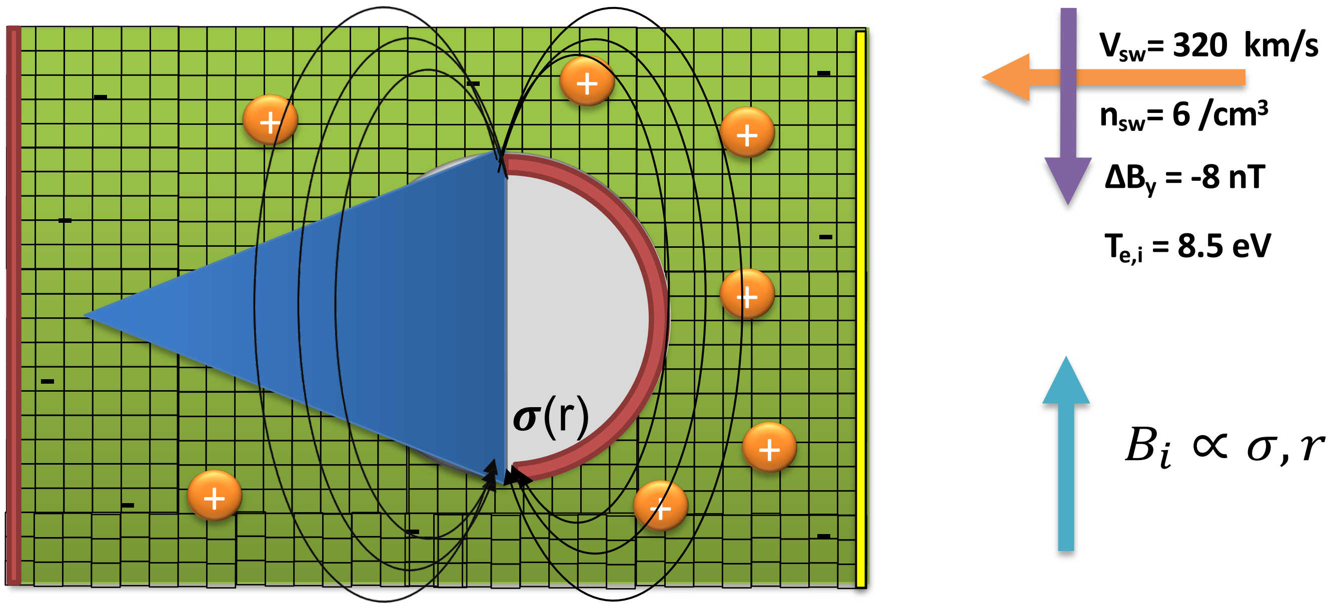
M_{ind} = 10^16 A m^2

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

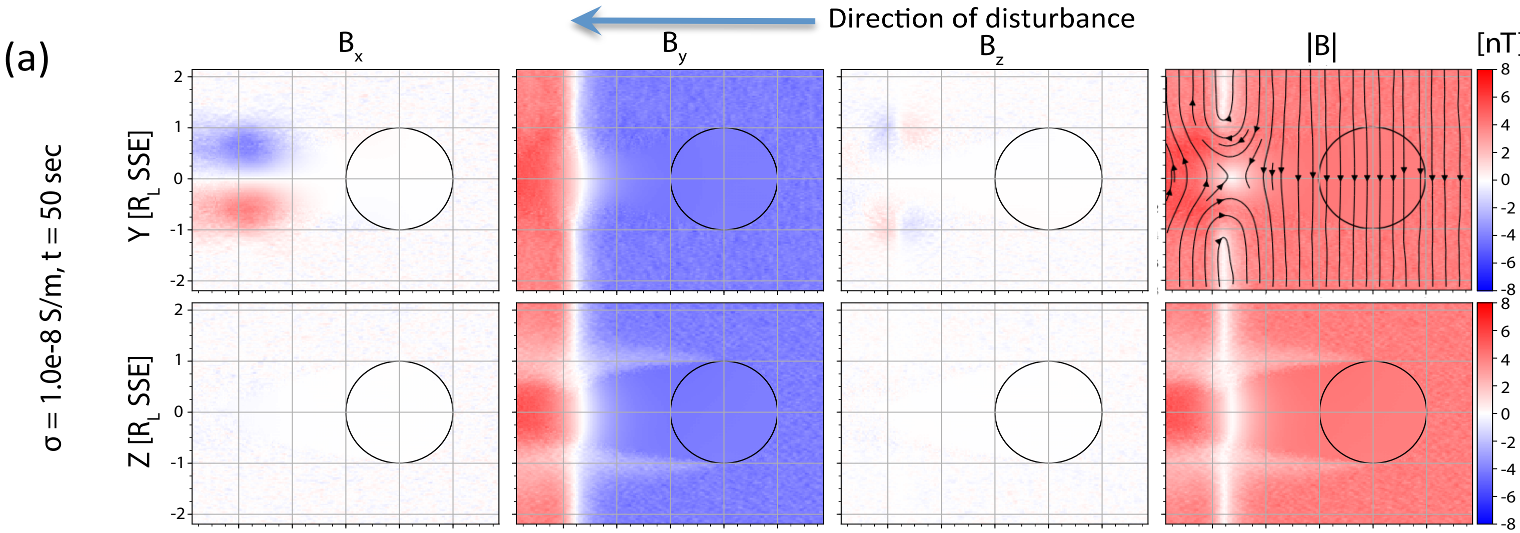
General Case, Perpendicular

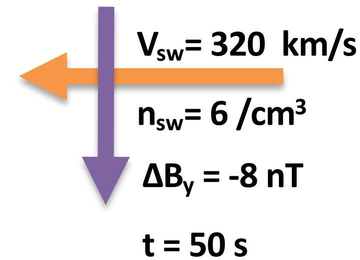


- Cell size: 50 km (~0.028 R_L)
- 16 macroparticles (only protons) per cell
- t_{step} = 0.001 s
- 0 < t < ~300 s, t=24 s IMF discontinuity
- σ_1 = 1.0 e – 8, 1.0 e – 4, 1.0 e – 3 [S/m]

- 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)
- Model captures inductive and plasma response self-consistently
- SSE Coordinate System: Selenographic Solar Ecliptic (+X_{SSE} points towards the sun)

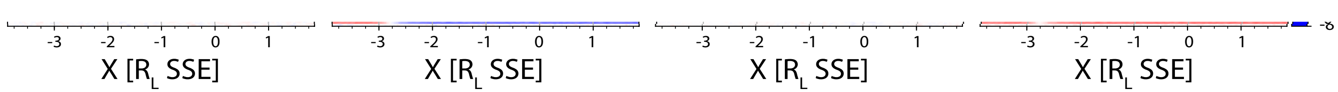
Results: Single Time Step





SSE Coordinate System (+X_{SSE} points towards the sun)

R_L=1850 km



Fuqua Haviland et al., 2019. GRL.

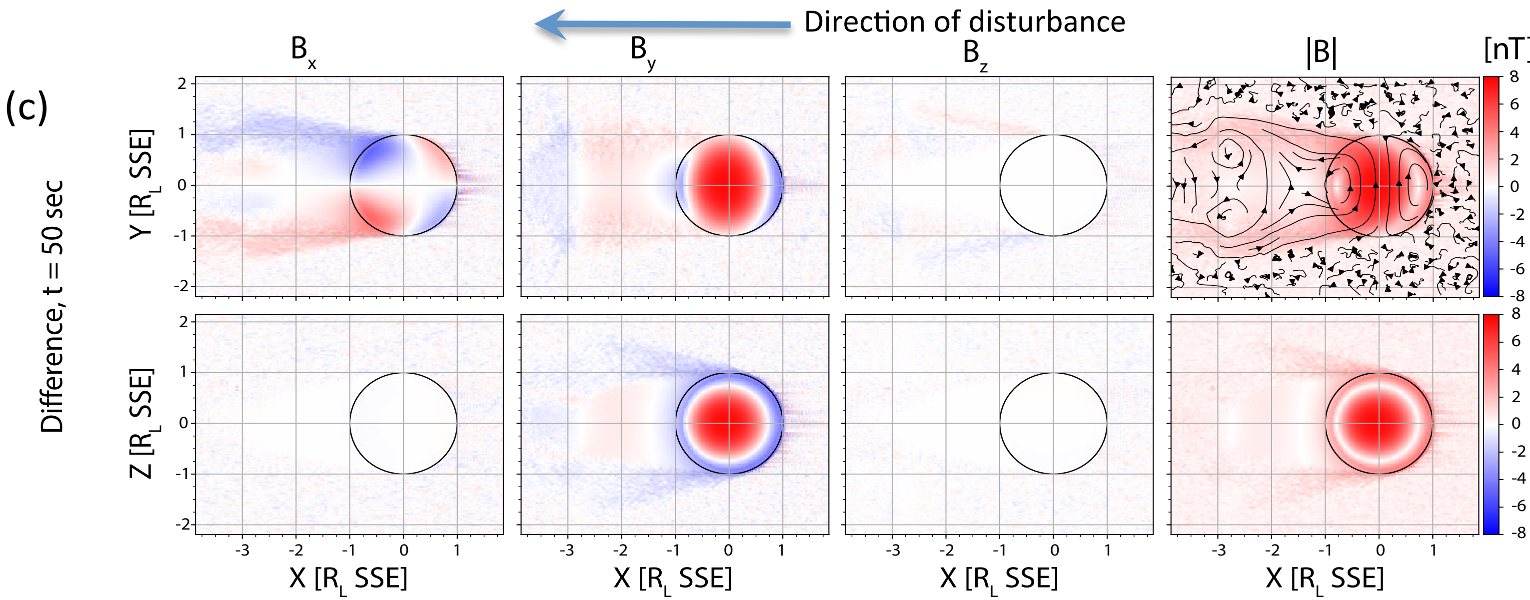
Results: Single Time Step (con't)

V_{sw}= 320 km/s

n_{sw}= 6 /cm³

ΔB_y = -8 nT

t = 50 s

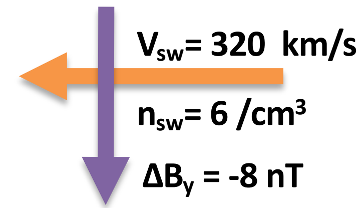


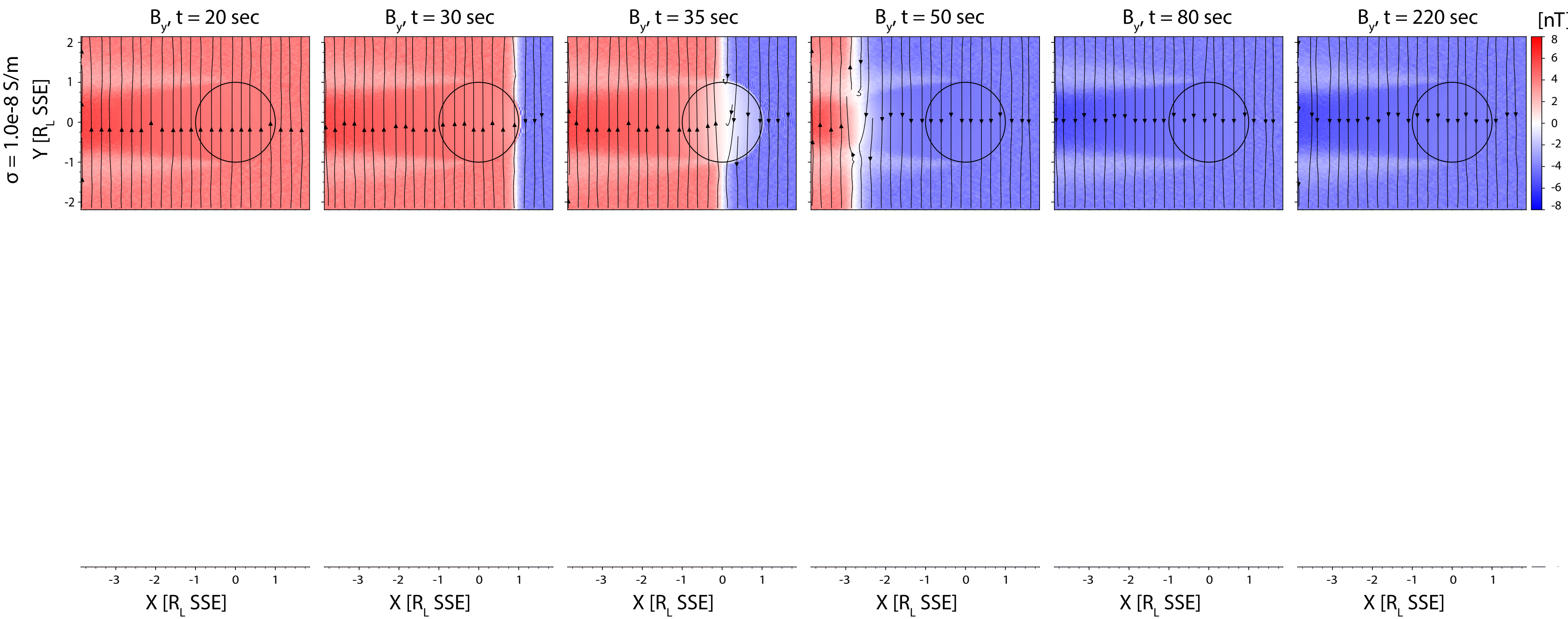
Residual Difference = **Conductive Case** - **Resistive Case**

(Plasma Effects Only)

Fuqua Haviland et al., 2019. GRL.

Results: Time Dependence

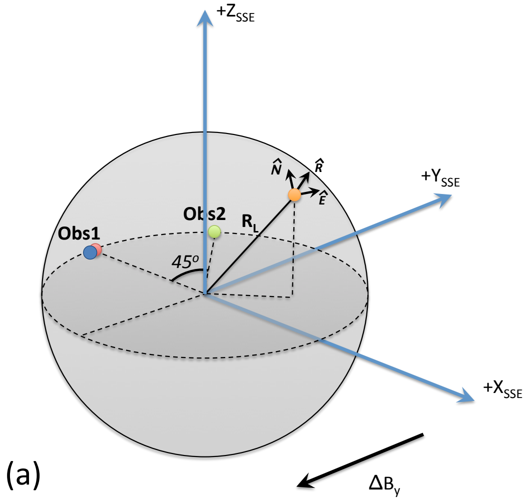


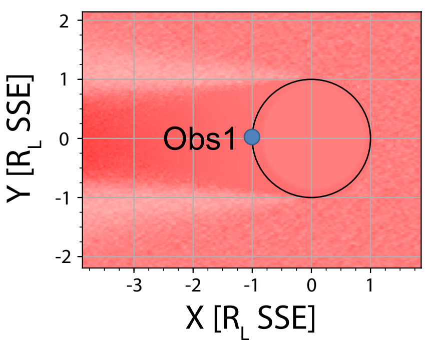


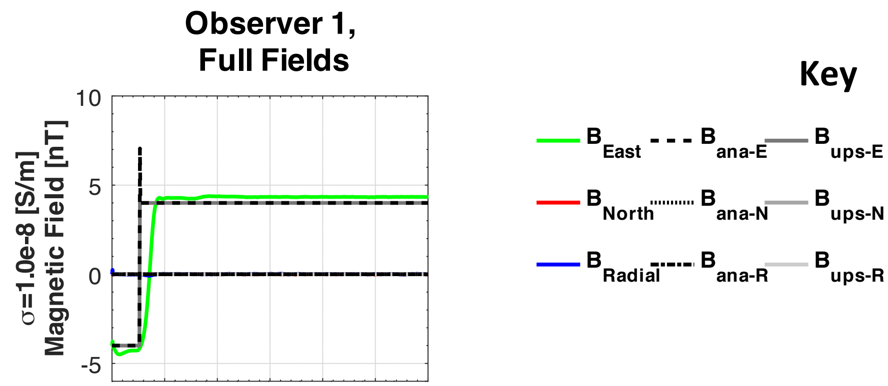
SSE Coordinate System (+X_{SSE} points towards the sun)

R_L=1850 km

Results: Case Study 1 Time Series

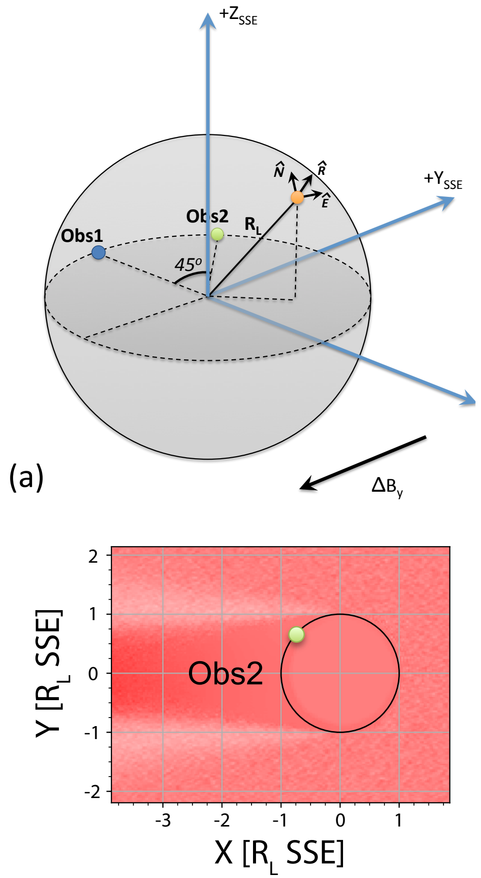


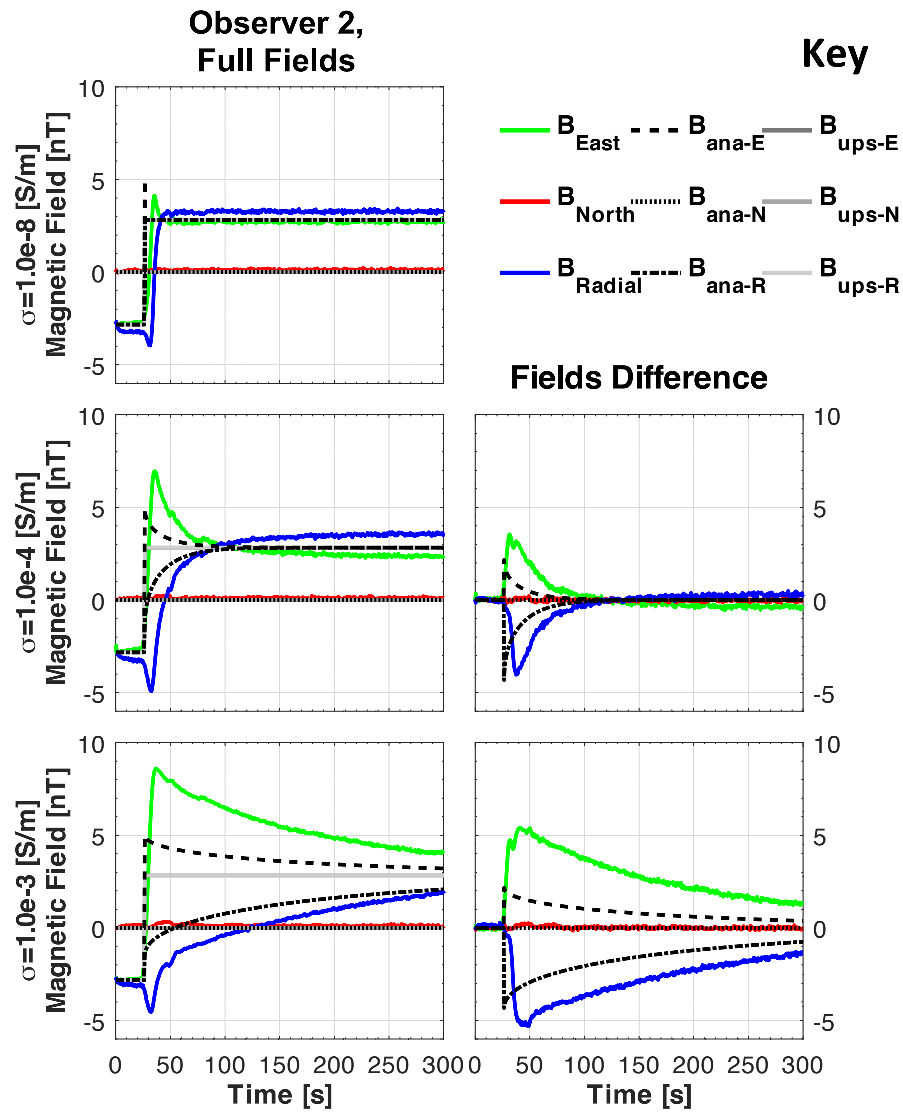




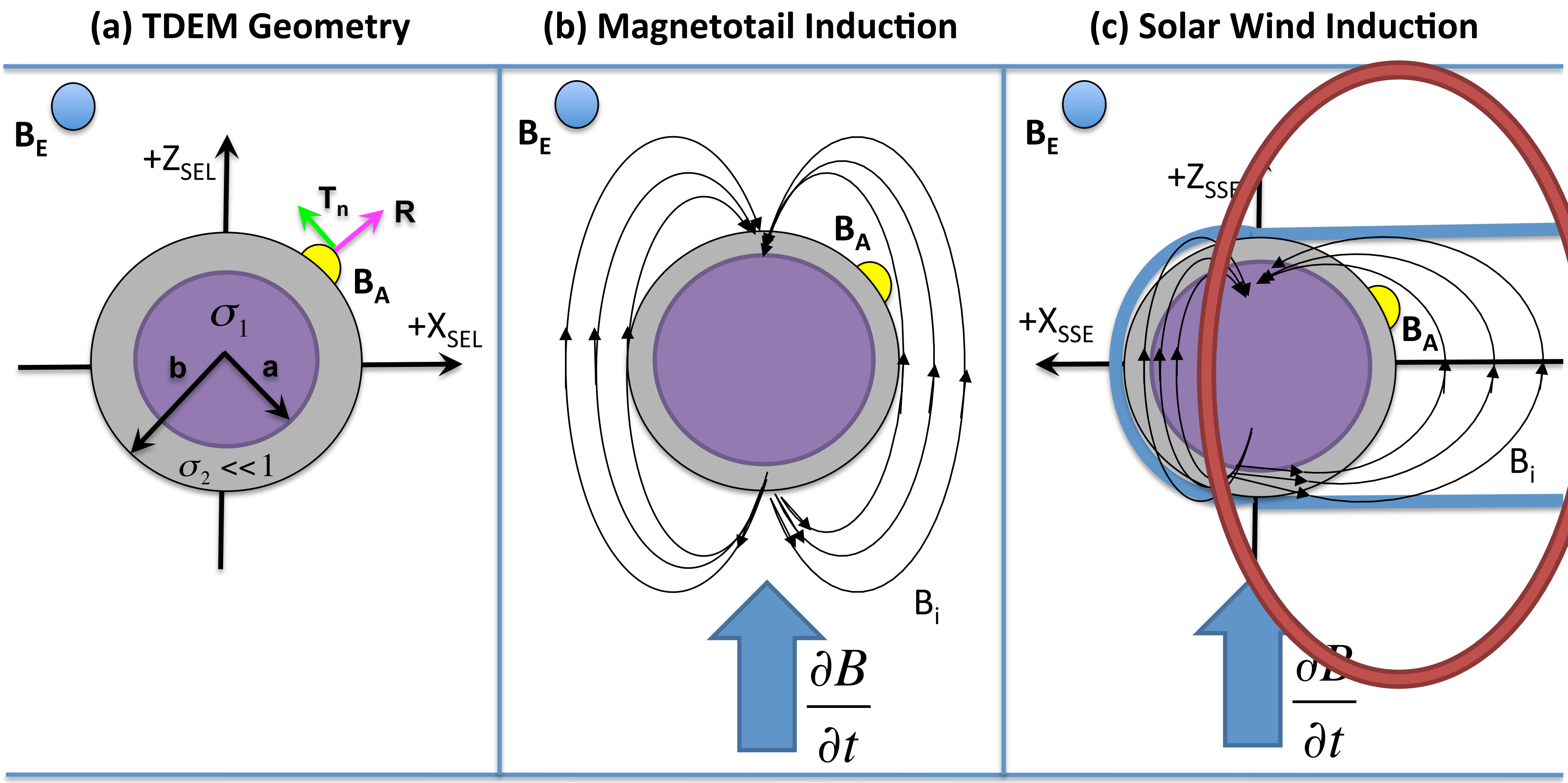
Fuqua Haviland et al., 2019. GRL.

Results: Case Study 2 Time Series





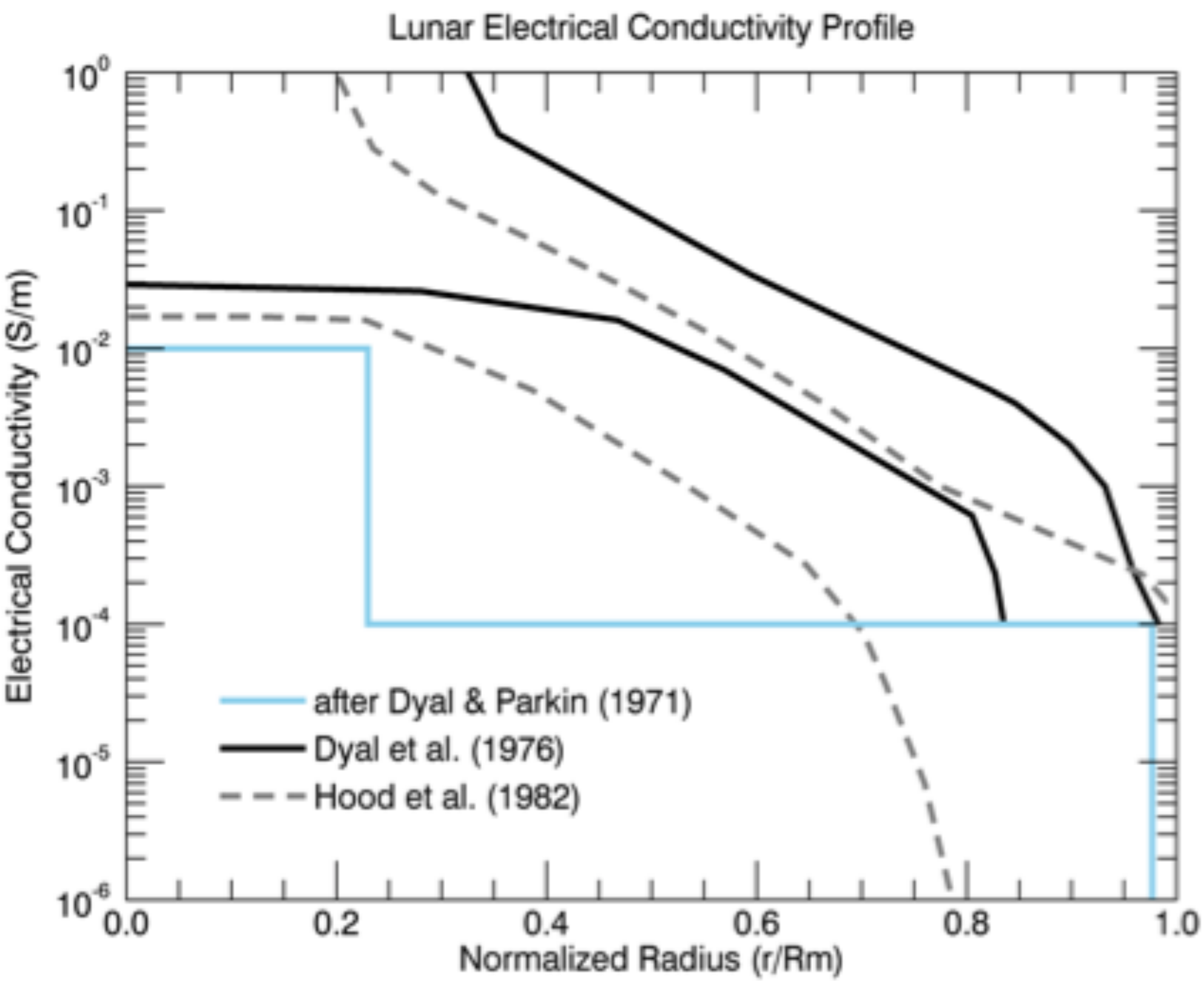
Lunar Electromagnetic (EM) Sounding Transient Response Method



Fuqua Haviland et al., 2019. ASR

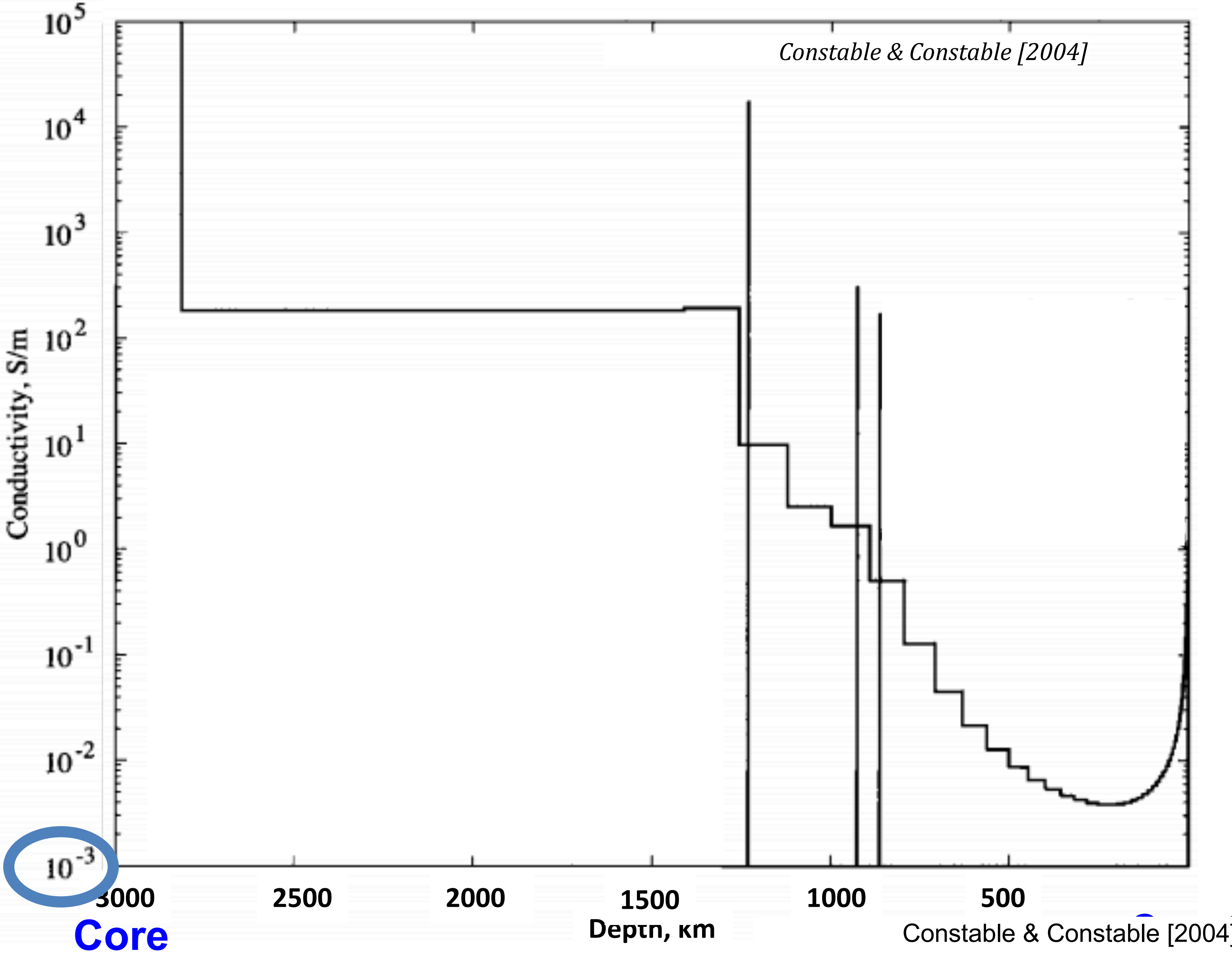
The Apollo Picture

Electrical Conductivity Profile



Fuqua Haviland et al., 2019. ASR.

Elec. Conductivity Profile - Earth

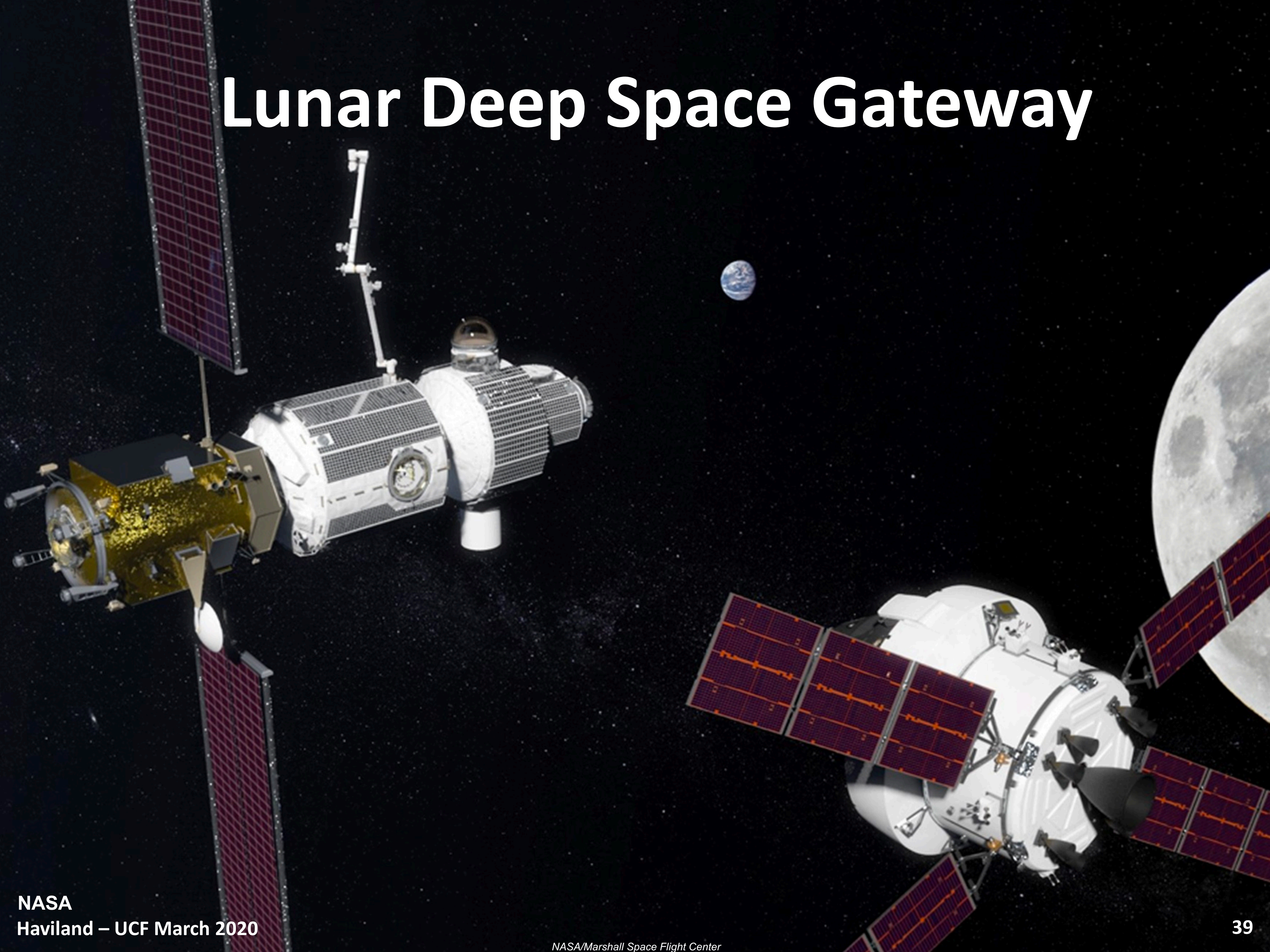


Constable & Constable [2004]

Conclusion & Future Work

- Vacuum theory alone is not able to fully characterize nightside induced fields.
- Plasma hybrid model characterizes plasma currents which vary depending on solar wind conditions
- For the first time, we observe wake and induced field coupling. Redefining Apollo era assumption about wake field confining induced field within cavity.
- Additional work is needed to isolate induction with magnetometer observations (Apollo, Lunar Prospector, Kaguya, THEMIS-ARTEMIS).
- Future magnetometer observations at or near the surface of the Moon will improve electrical conductivity constraints with TDEM Sounding.

Lunar Deep Space Gateway



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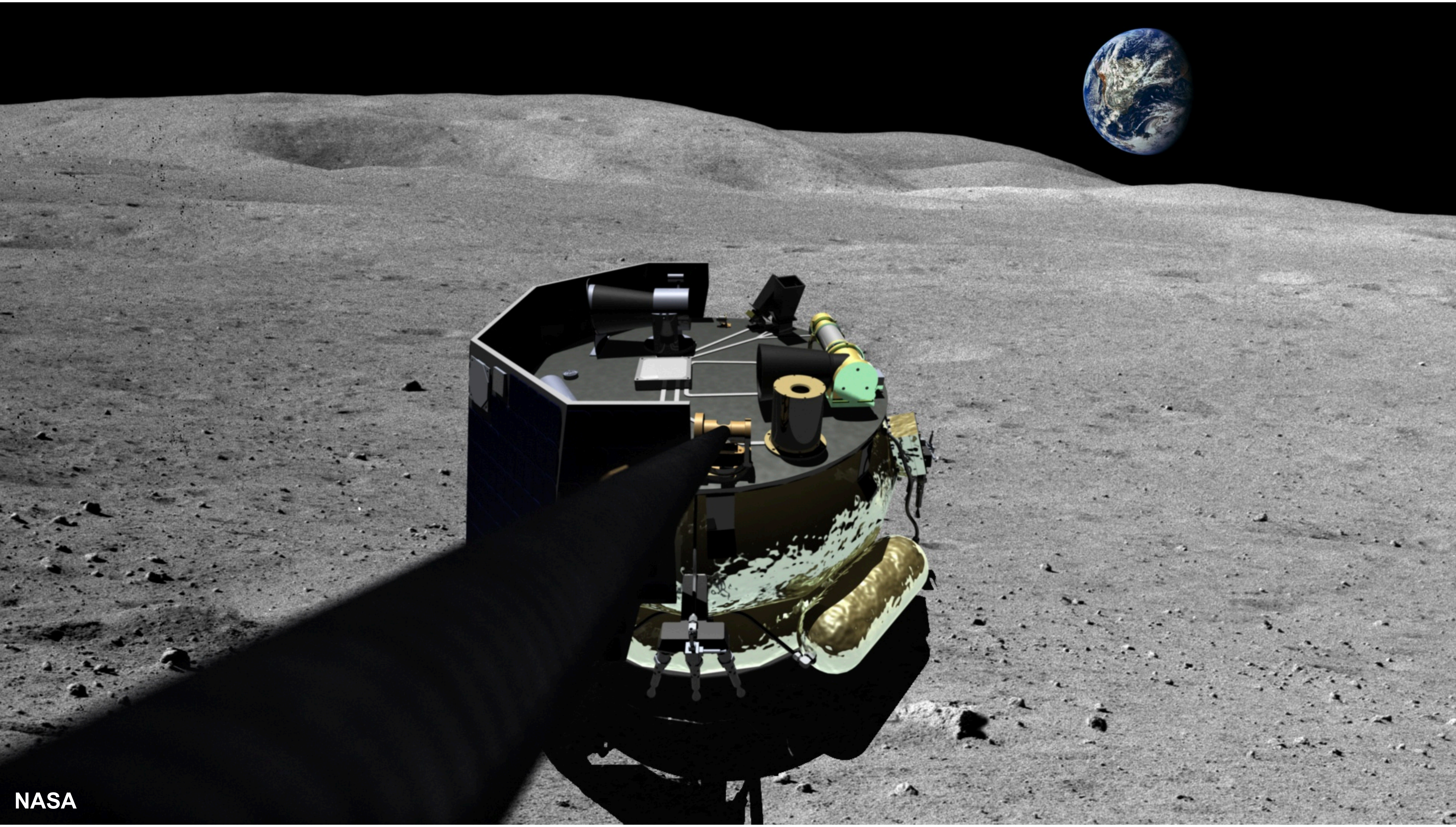
Commercial Lunar Payload Services (CPLS)



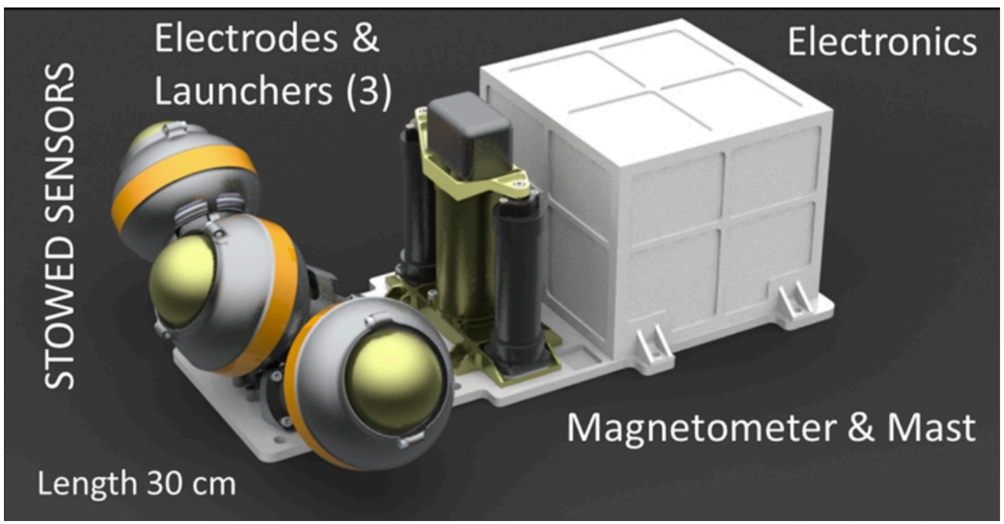
NASA/Marshall Space Flight Center

Lunar Geophysical Network (LGN)

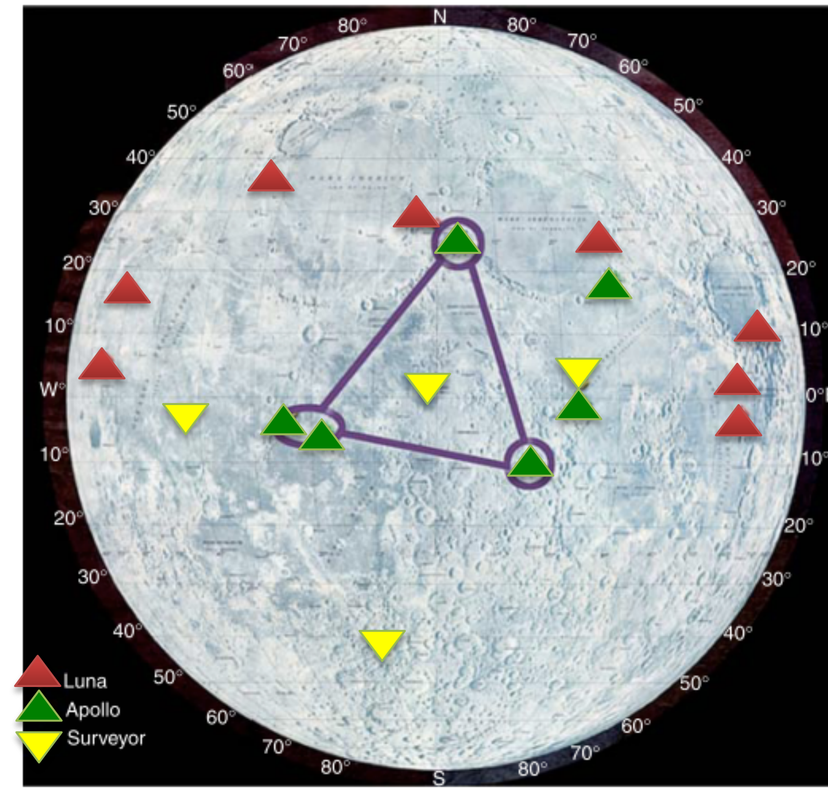
Mission Objectives: to improve the state of knowledge of the lunar interior in terms of composition, structure, temperature.

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, Grimm et al. 2020



Lognonné, 2007, 10.03 Planetary Seismology, p. 73

InSight Potential EM Sounding at Mars

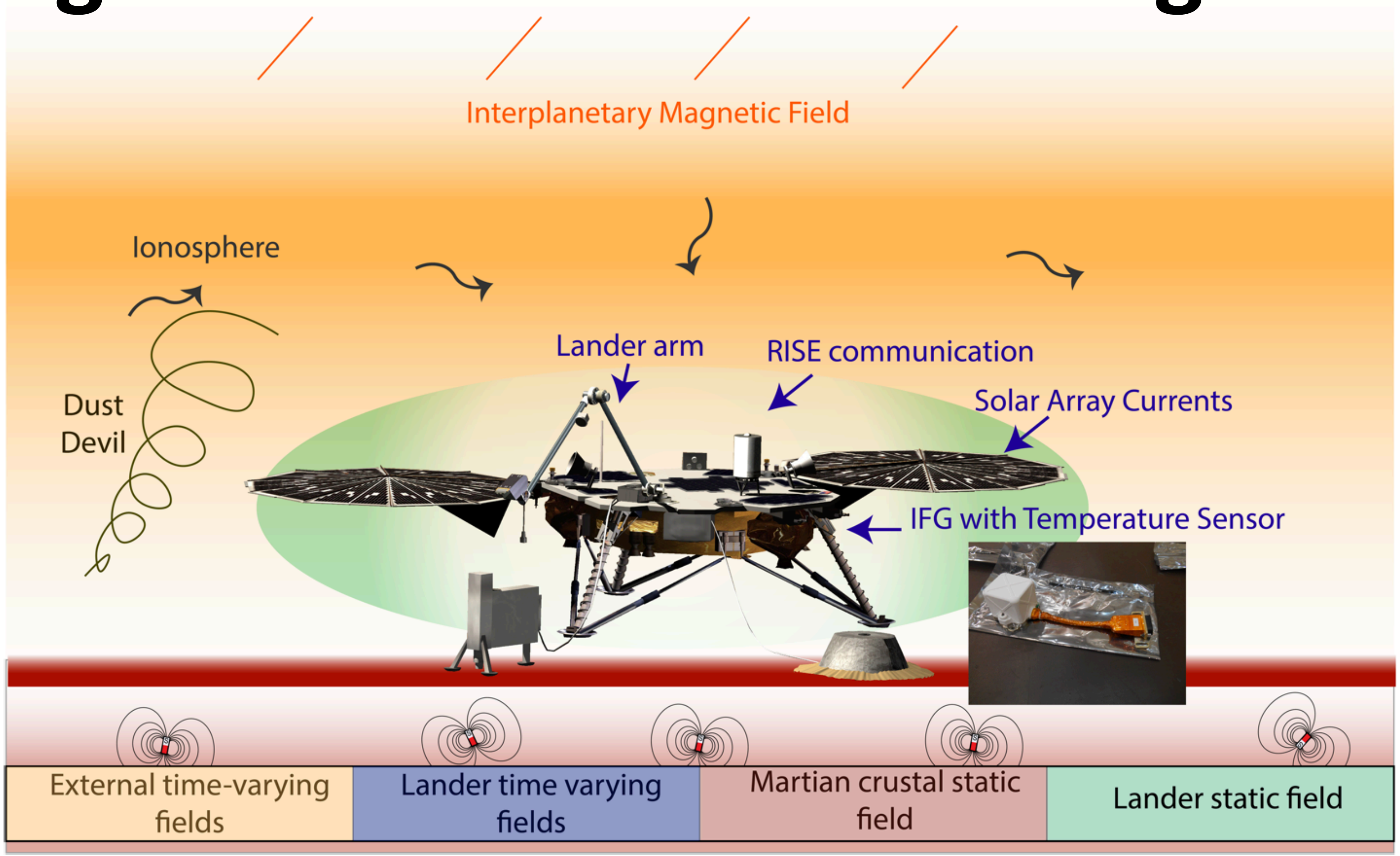


Fig. S1 | Contributions to the Magnetic Field Measured by the IFG. Time-varying fields are either of external origin (orange), including the interplanetary magnetic field, ionospheric currents and weather events such as dust devils; they can also be of lander origin (blue), e.g., due to movement of the arm, RISE communications, Solar Array Currents, or martian temperature variations, measured by the temperature sensors on the lander. The martian static crustal field (red) results from crustal magnetization, represented schematically here as subsurface dipoles. A DC field is also associated with the lander itself (green).

Johnson et al., 2020. Nature Geo.

Neutron Measurements at the Lunar Surface (NMLS)

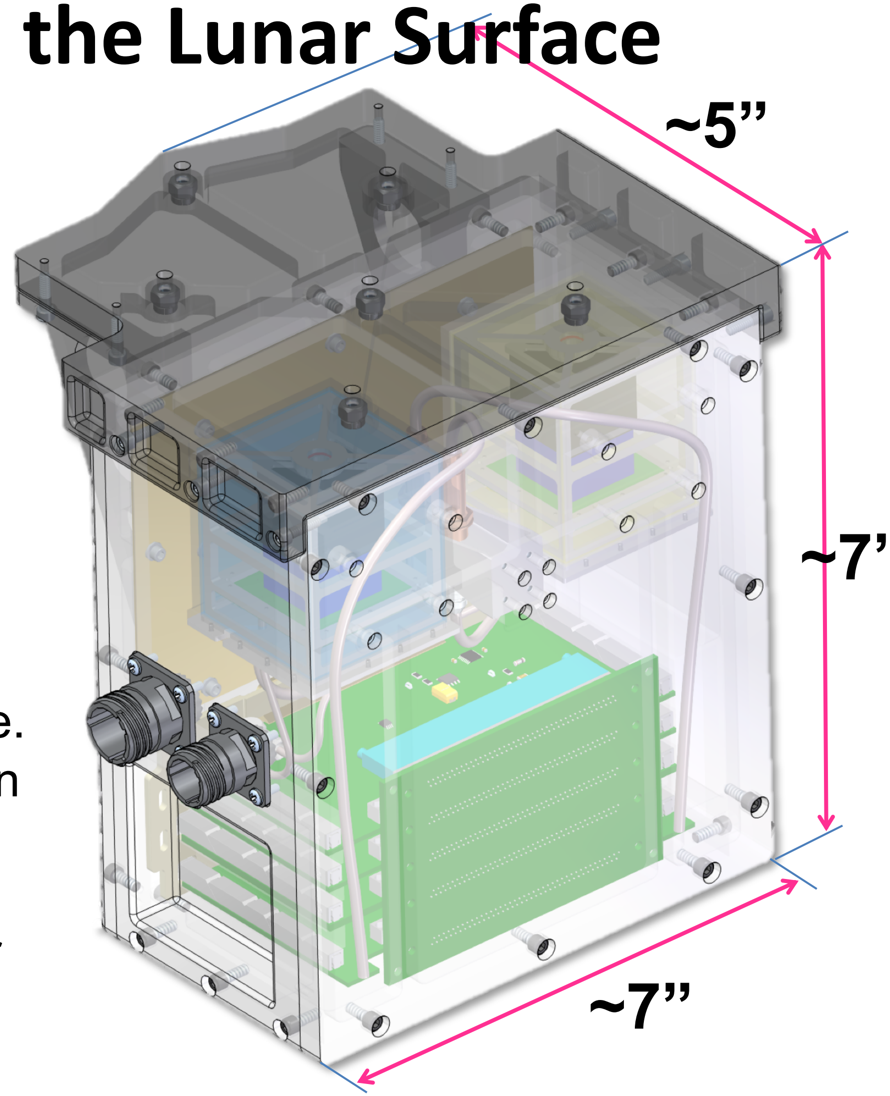
Mission Objectives:

1. Characterize the neutron radiation environment.
2. Provide in-situ ground truth for calibrating orbital data.
3. Provide constraints on composition (e.g., science & ISRU).
4. Monitor hydrogen cycle through lunar day.

Project Description:

- Provide neutron counts at the lunar surface.
    - Deliver thermal and epithermal neutron rate counters using composite ^{6}Li-doped scintillators.
    - Operate for ~8 Earth days, (~1/2 lunar daylight).
- Based on flight heritage (developed at MSFC), FNS instrument currently operating on the ISS, and in development for Gateway.

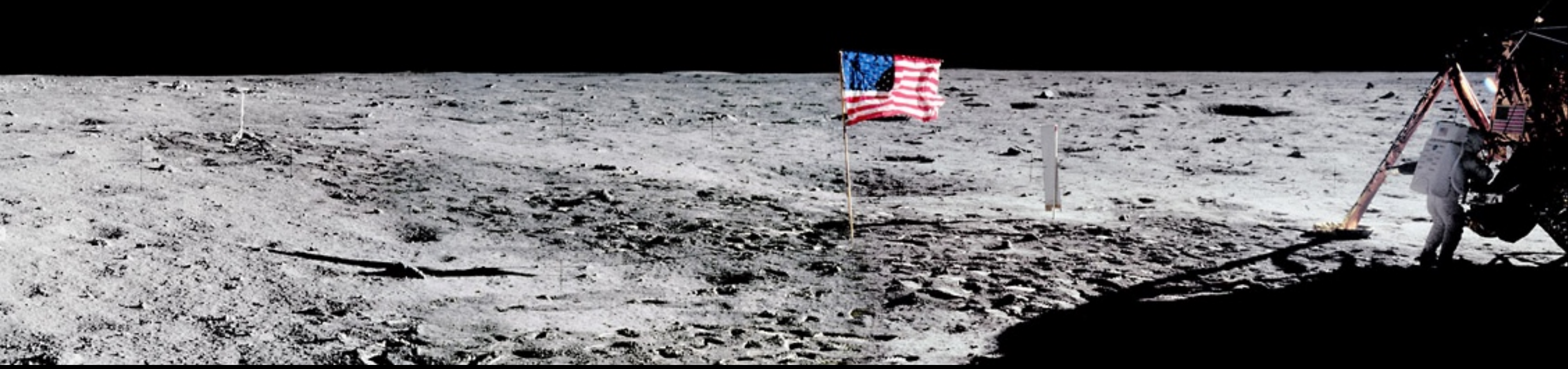
Funding: Lunar Discovery and Exploration Program (LDEP)



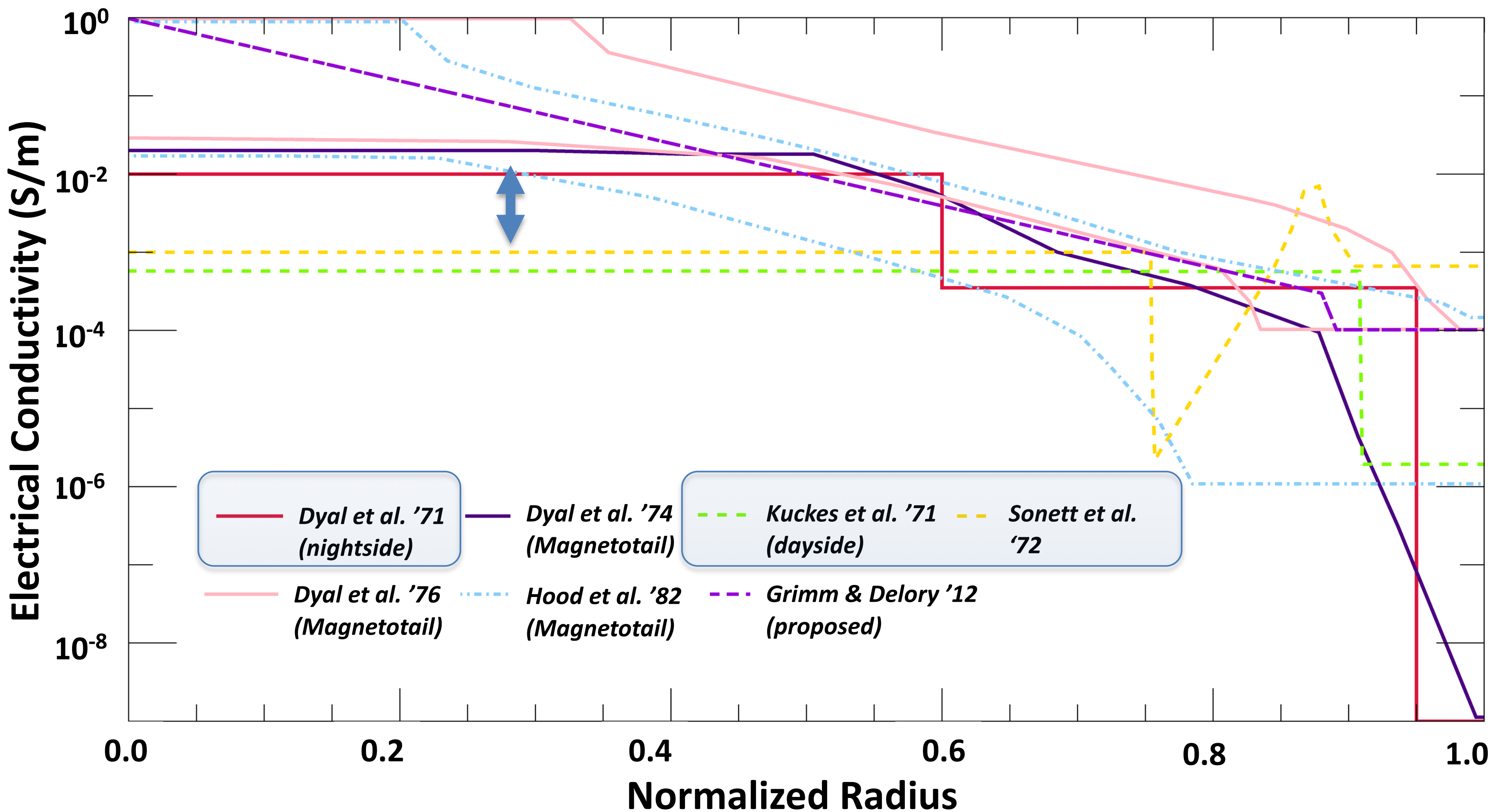
NMLS Mechanical Model

Mass: ~4 kg
Data rate: 10 bps
Ave Power: 4.8 W
Peak Power: 10 W

Questions?



Summary of Apollo Lunar Electrical Conductivity Profiles



Ref: Dyal et al., 1971