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
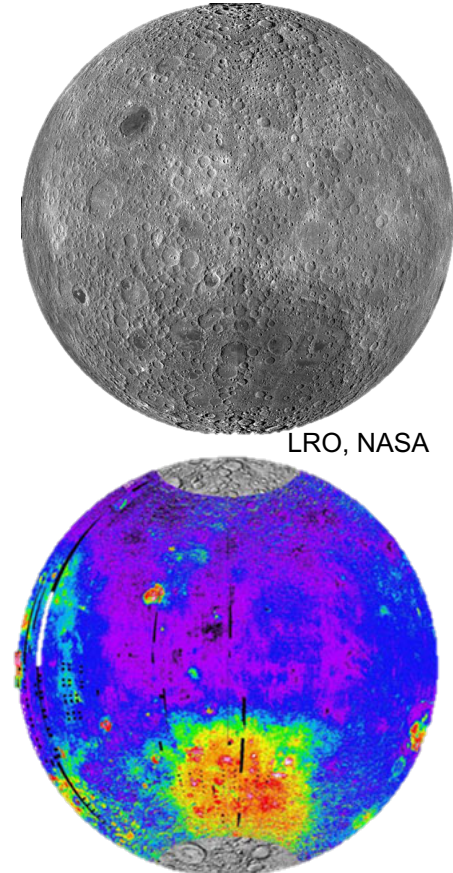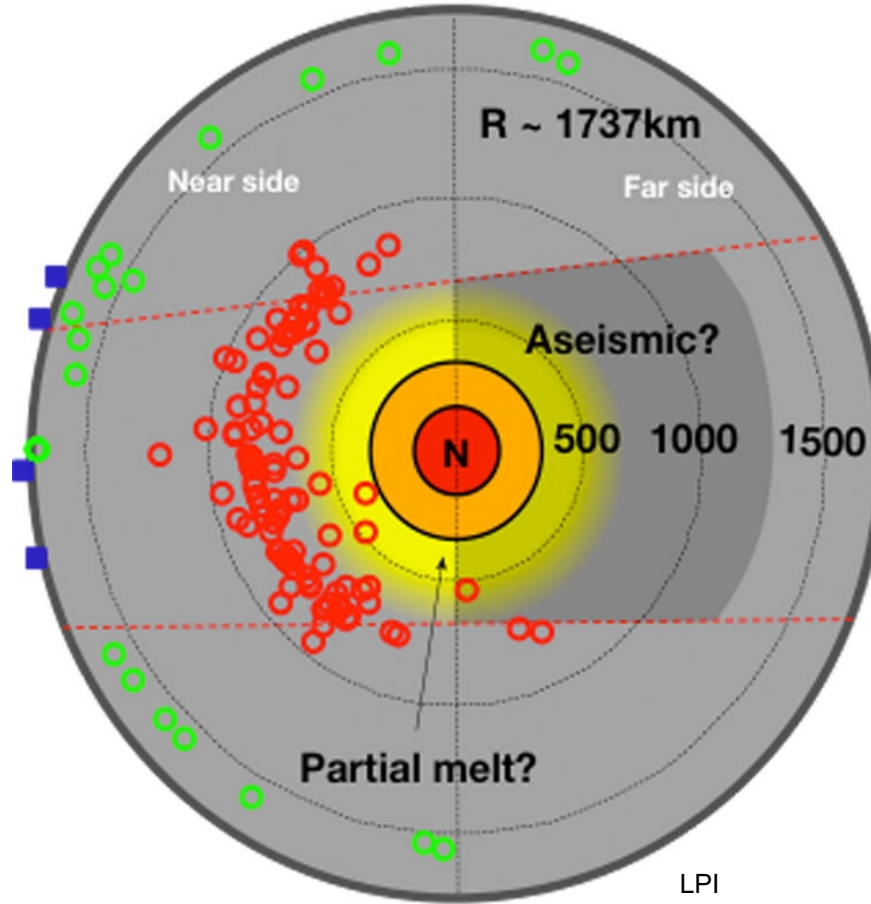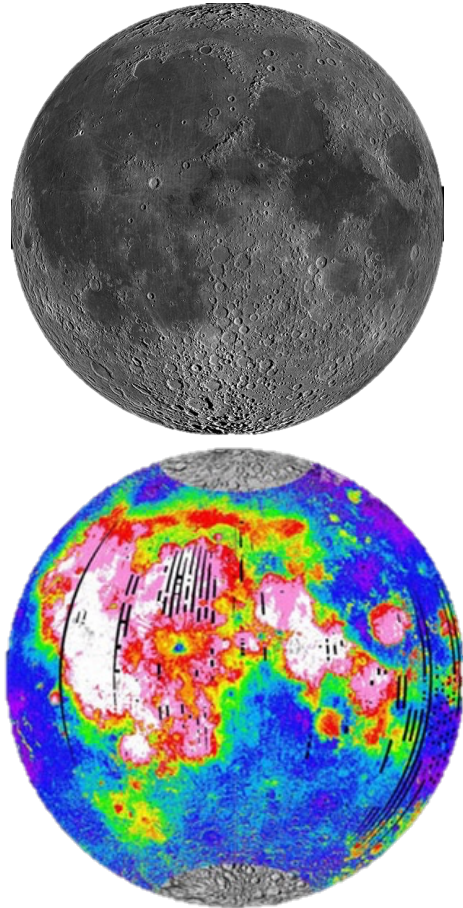
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Driving Science Question

Near Side

Far Side

Equatorial Cross-section

R ~ 1737km

Near side   Far side

Aseismic?

N   500 1000 1500

Partial melt?

LPI

LRO, NASA

Hiesinger & Head, 2006

■ Apollo station
○ Deep moonquake nest
○ Shallow moonquake event

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

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Lunar Origin Theories
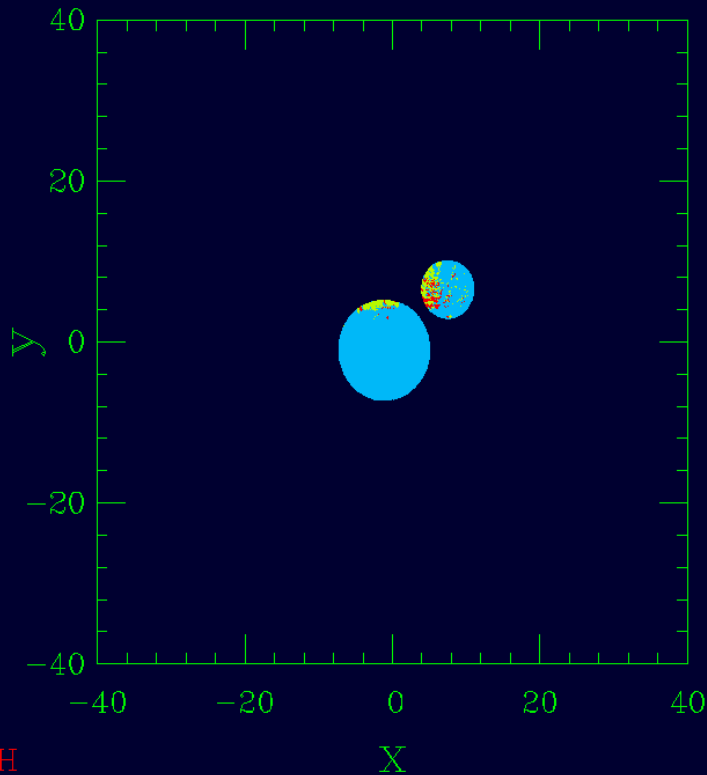
Canup et al. 2016
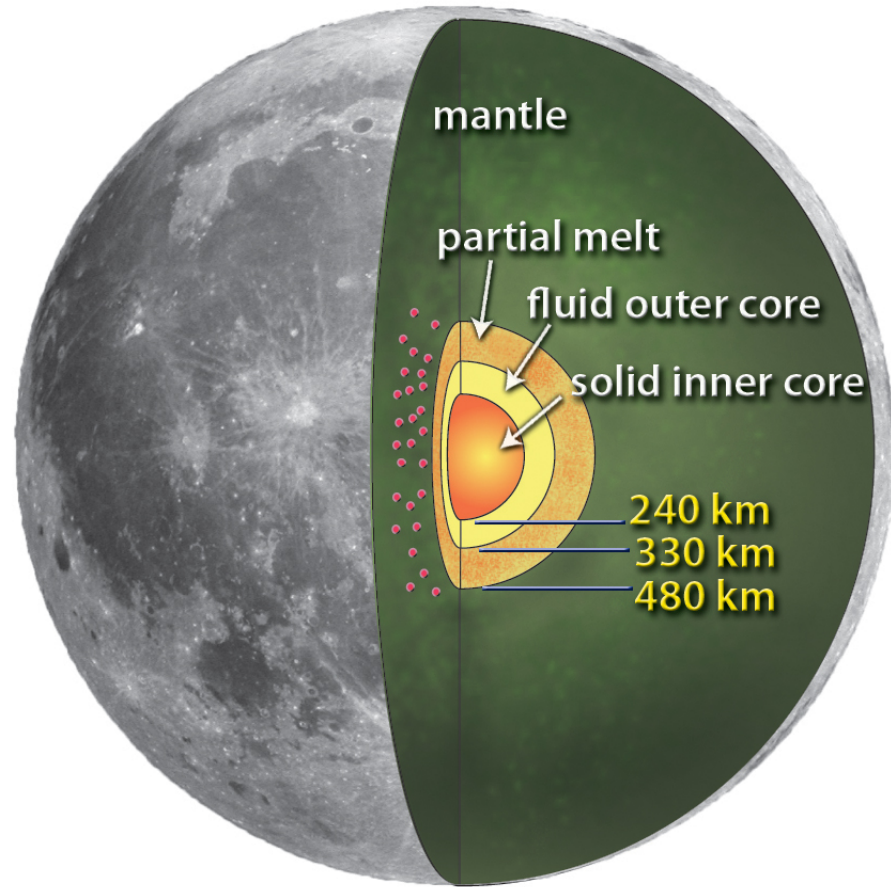
Weber et al., 2011

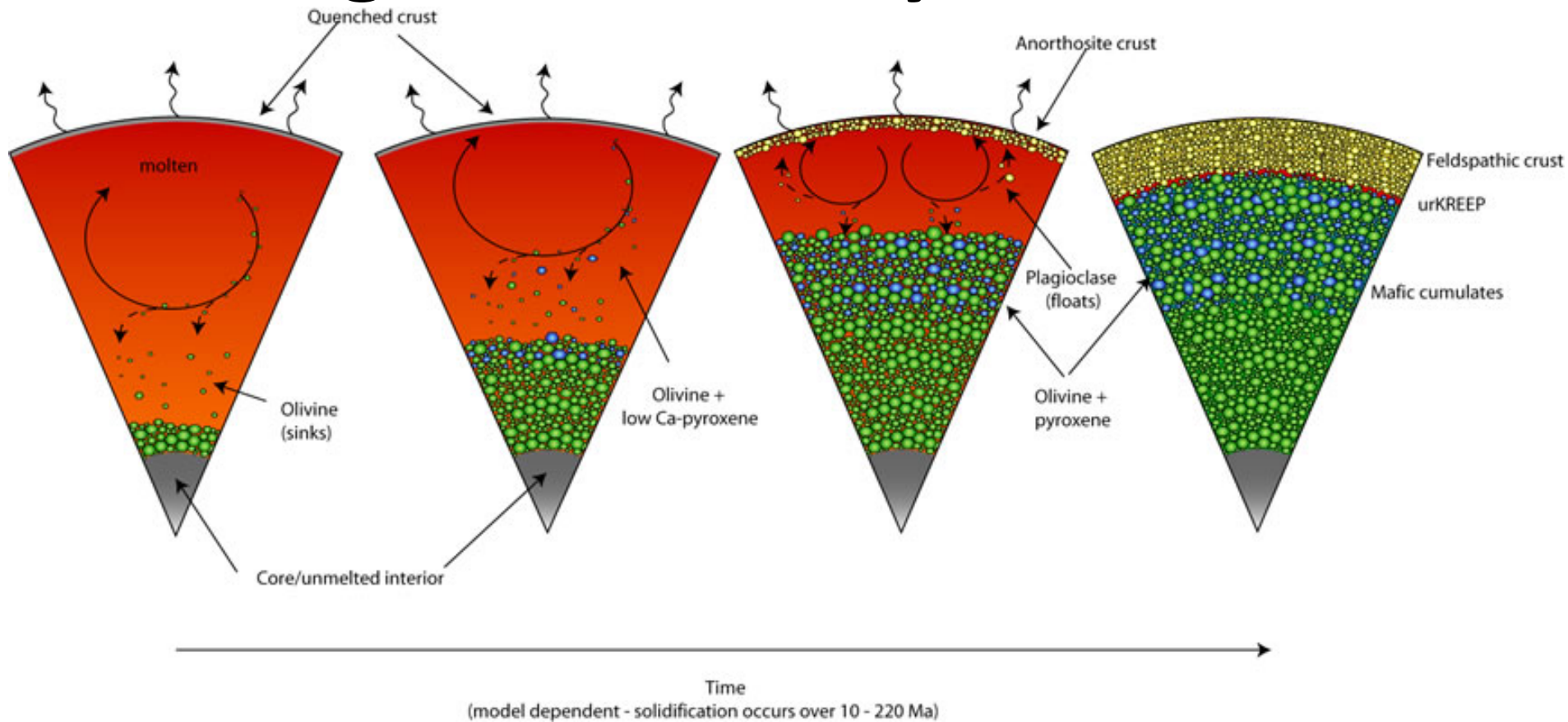## *The current state is key to constraining origin theories.*

NASA/Marshall Space Flight Center
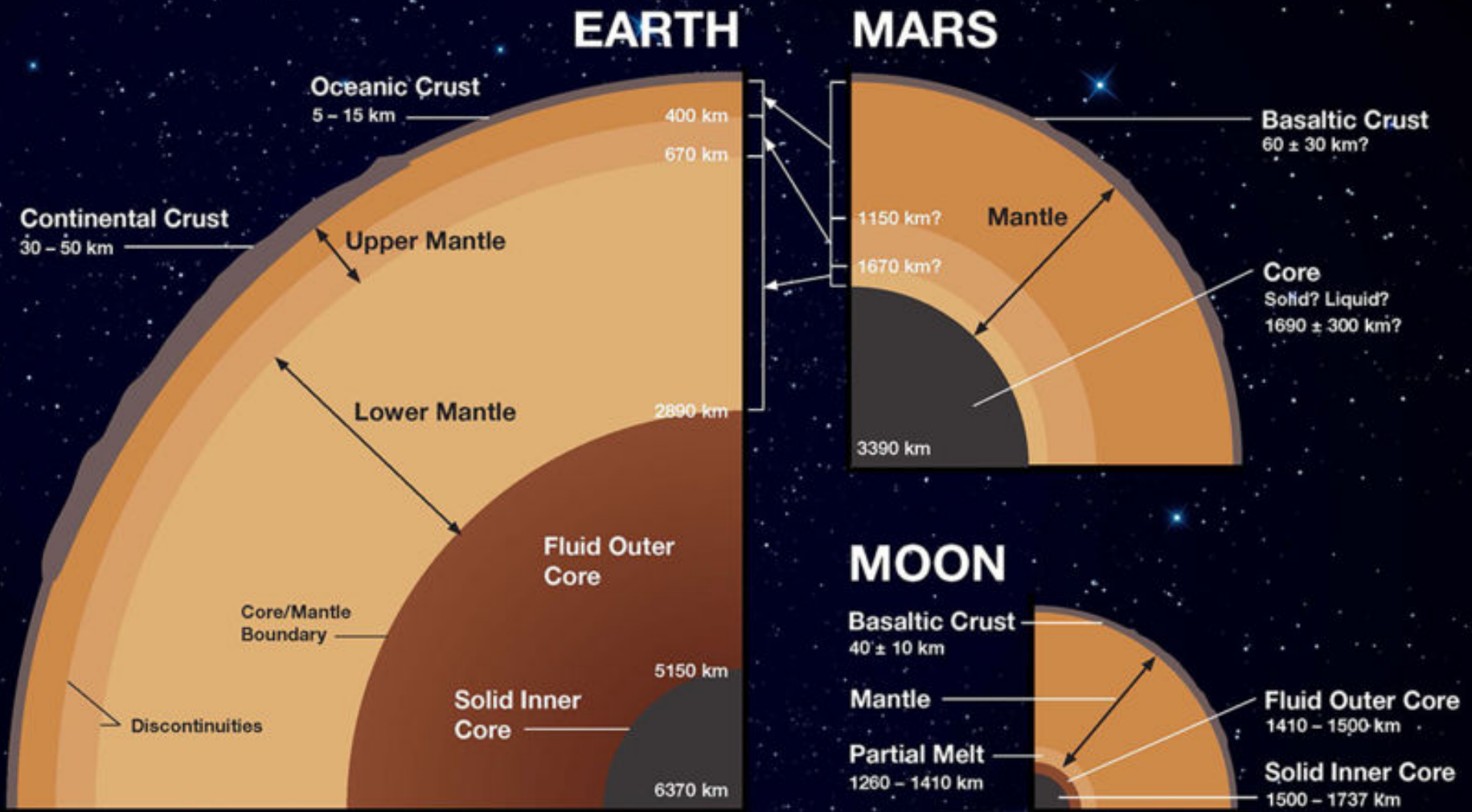
Magma Ocean Crystallization

Quenched crust

molten

Olivine (sinks)

Core/unmelted interior

Anorthosite crust

Olivine + low Ca-pyroxene

Plagioclase (floats)

Olivine + pyroxene

Feldspathic crust

urKREEP

Mafic cumulates

Time
(model dependent - solidification occurs over 10 - 220 Ma)

Image source: LPI

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

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Terrestrial Planet Interior Structure

EARTH

Oceanic Crust
5 – 15 km — 400 km
670 km

Continental Crust
30 – 50 km

Upper Mantle

Lower Mantle — 2890 km

Core/Mantle Boundary

Discontinuities

Fluid Outer Core

5150 km

Solid Inner Core

6370 km

MARS

Basaltic Crust
60 ± 30 km?

1150 km? Mantle
1670 km?

Core
Solid? Liquid?
1690 ± 300 km?

3390 km

MOON

Basaltic Crust
40 ± 10 km

Mantle

Partial Melt
1260 – 1410 km

Fluid Outer Core
1410 – 1500 km

Solid Inner Core
1500 – 1737 km

NASA

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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

Sun

Internal Structure:
- inner core
- radiative zone
- convection zone
- photosphere
- sunspot

plage

coronal mass ejection

corona

solar

heliosphere

Earth

Moon's Orbit

magnetic bow shock

solar wind

Sun

Earth

Earth's magnetotail

...sphere

...ere

...ere

magnetosheath

Stubbs, T. J., GSFC,
http://www.nasa.gov/topics/moonmars/features/magnetotail_080416.html

Image Source: NASA

NASA/Marshall Space Flight Center
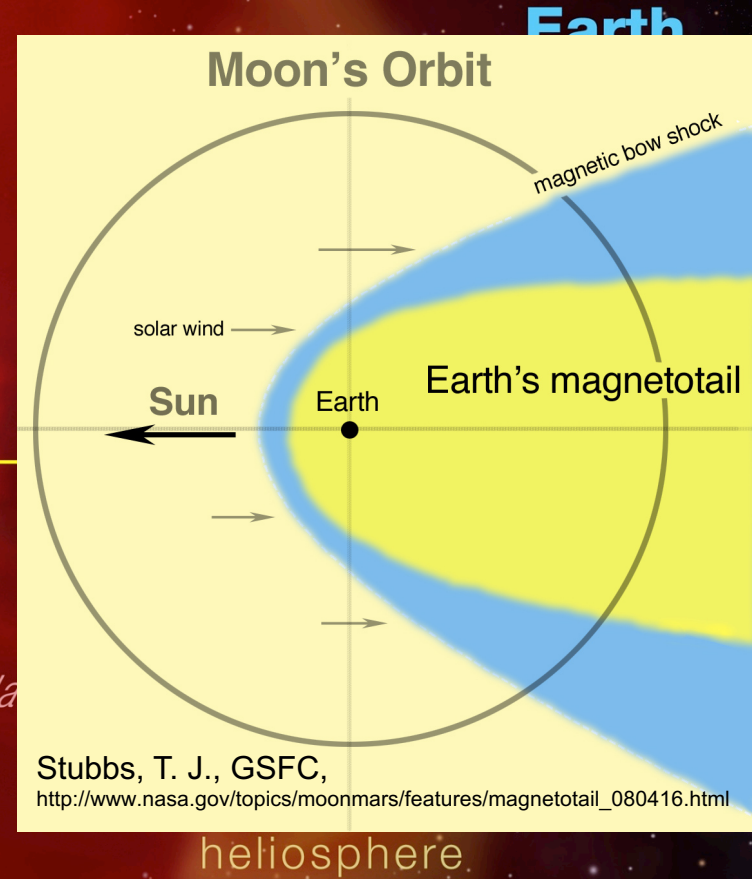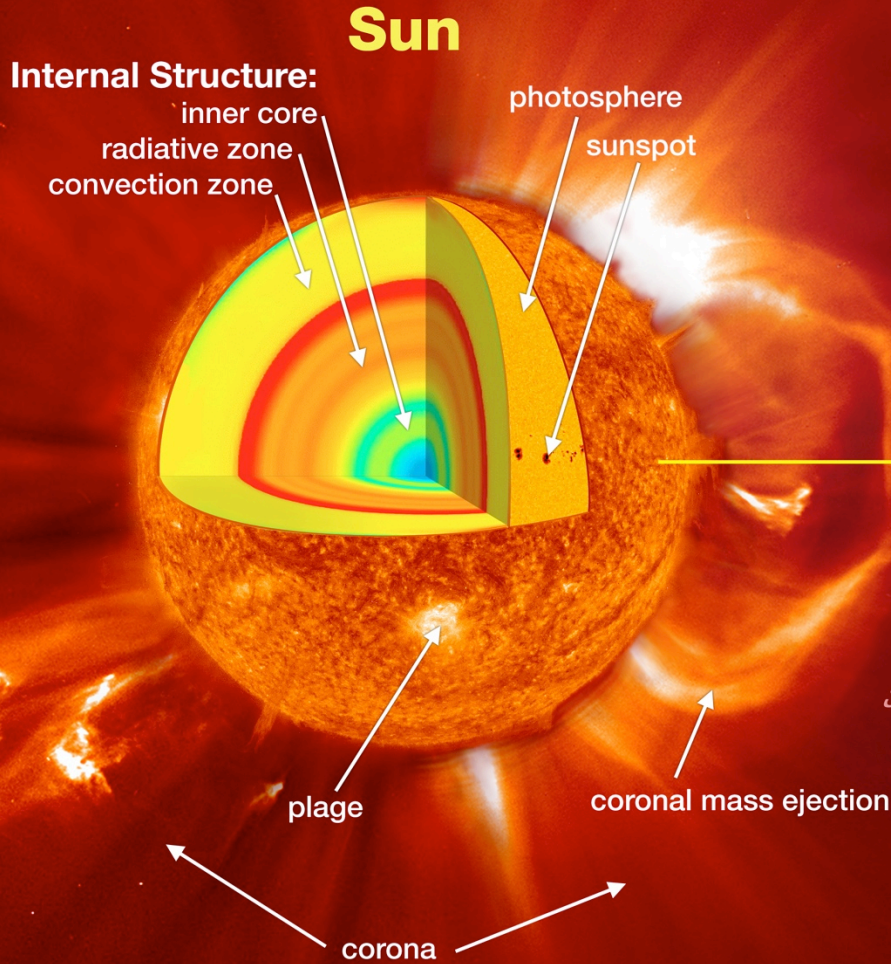
Solar Wind Space Plasma Environment

Image Source: G. Delory

NASA/Marshall Space Flight Center
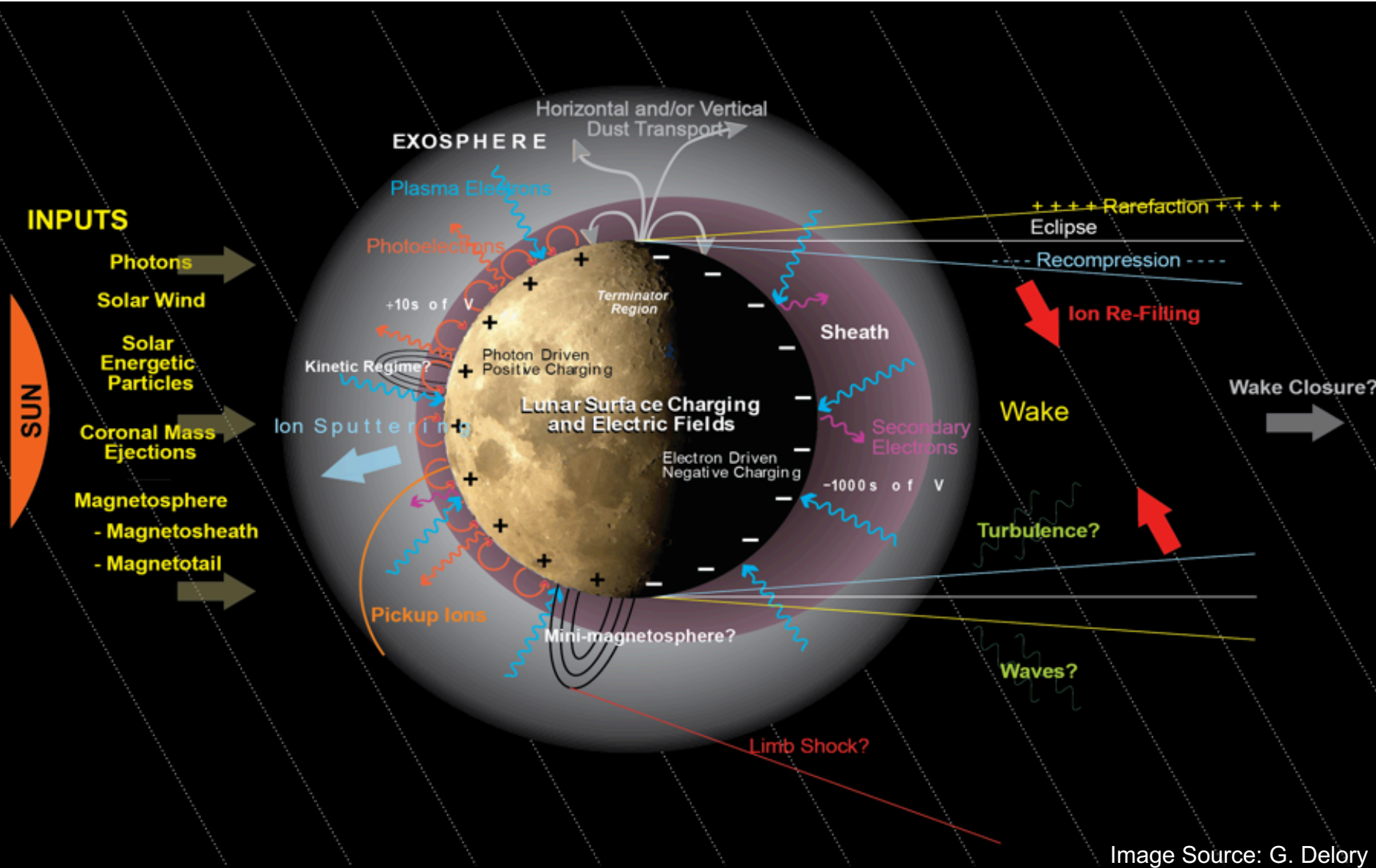
Lunar Crustal Magnetic Fields

Nearside
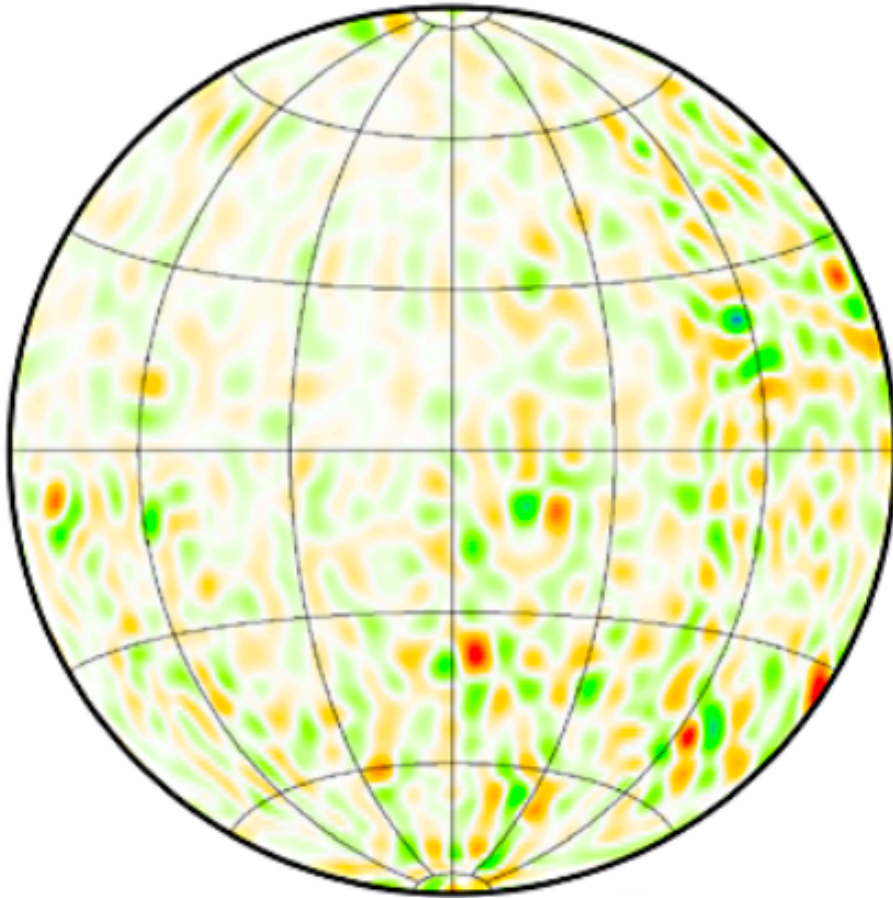
Farside
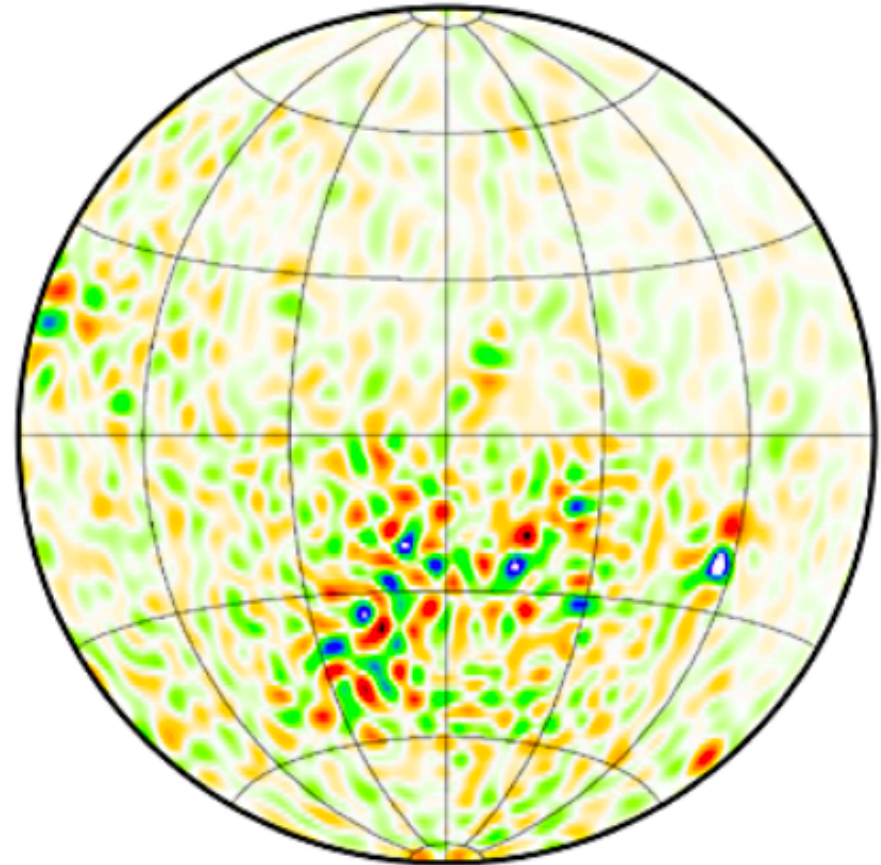
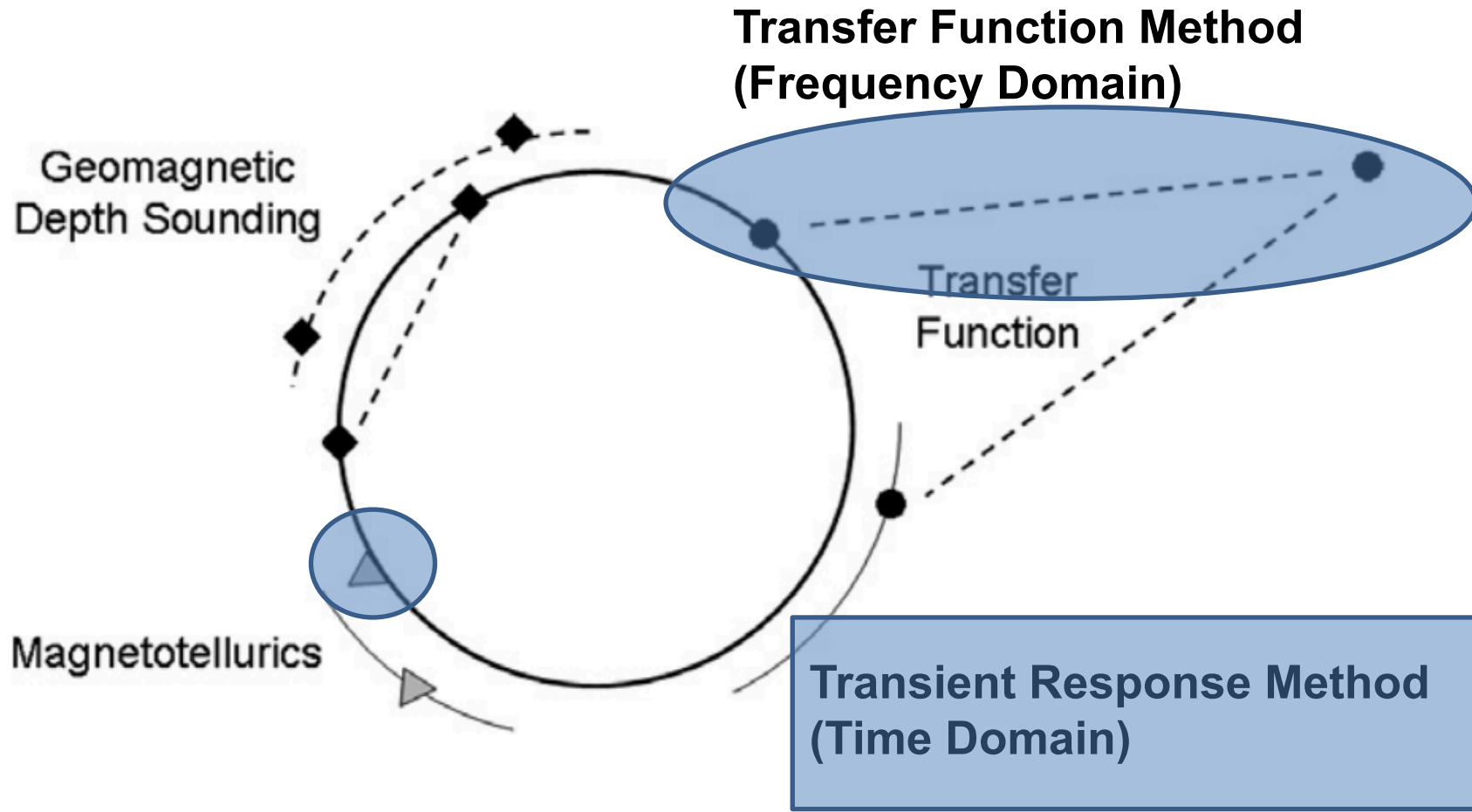Regions of weak crustal fields are prevalent.

Equivalent surface Field Strength.

-20nT   0   20nT
-5nT   0   5nT
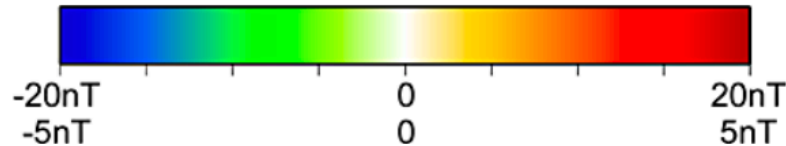
Tsunakawa et al., 2010

Asymmetric Plasma Confinement

Photons

Solar Wind

Solar Energetic Particles

Coronal Mass Ejections

SUN

$$\frac{\partial B}{\partial t}$$
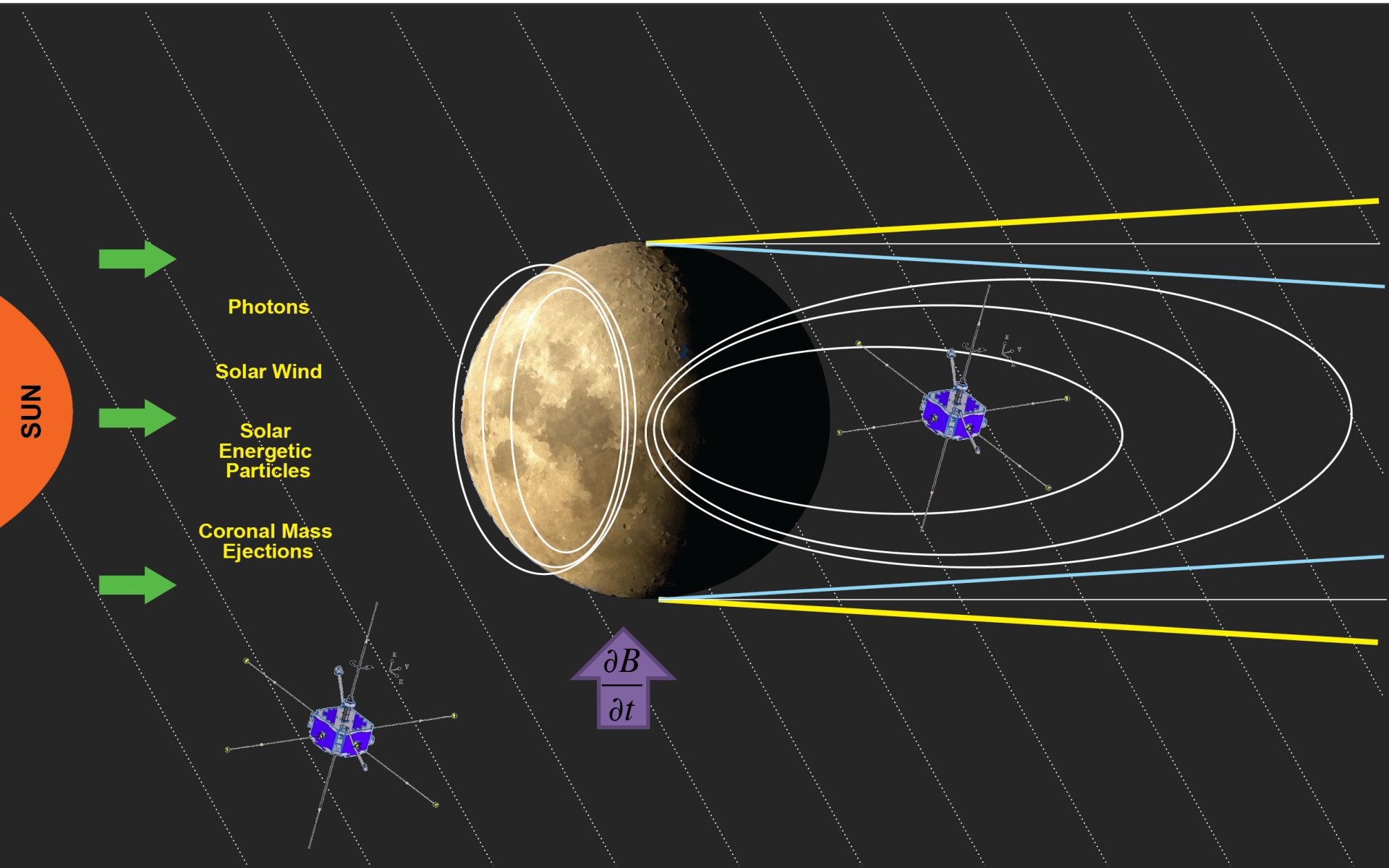
Planetary EM Geophysical Methods

Transfer Function Method (Frequency Domain)

Geomagnetic Depth Sounding

Transfer Function

Magnetotellurics

Transient Response Method (Time Domain)

Grimm and Delory, 2012

Lunar Electromagnetic (EM) Sounding Transient Response Method

(a) TDEM Geometry
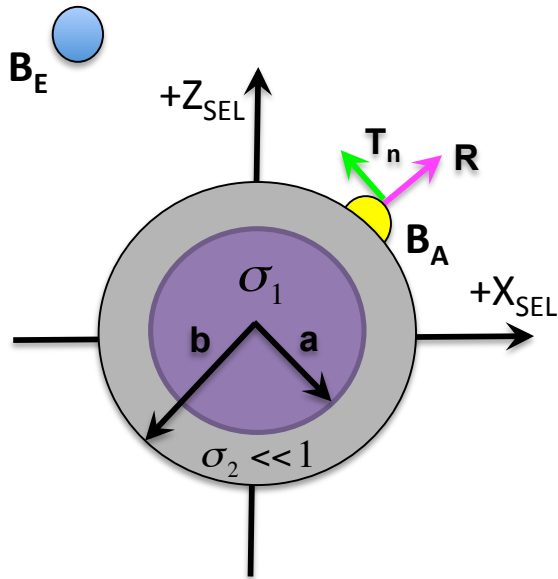
(b) Magnetotail Induction
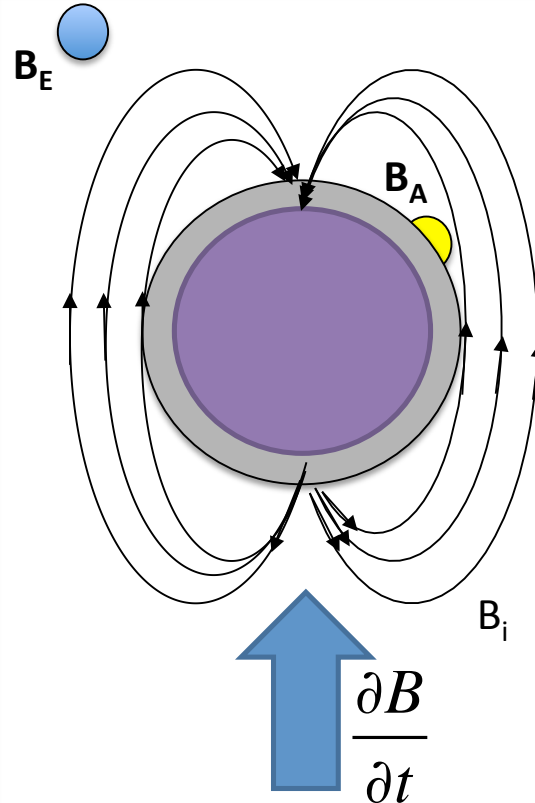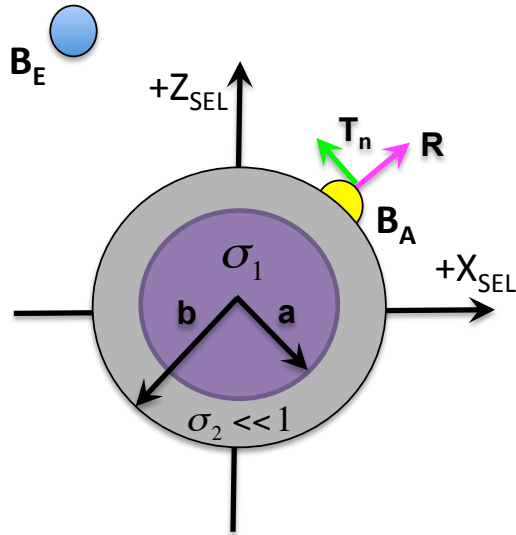
(c) Solar Wind Induction
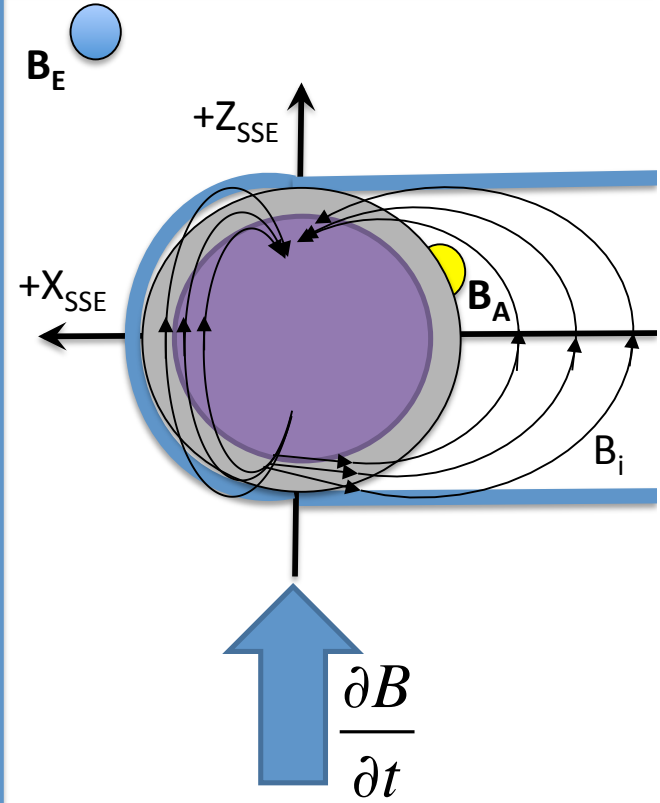
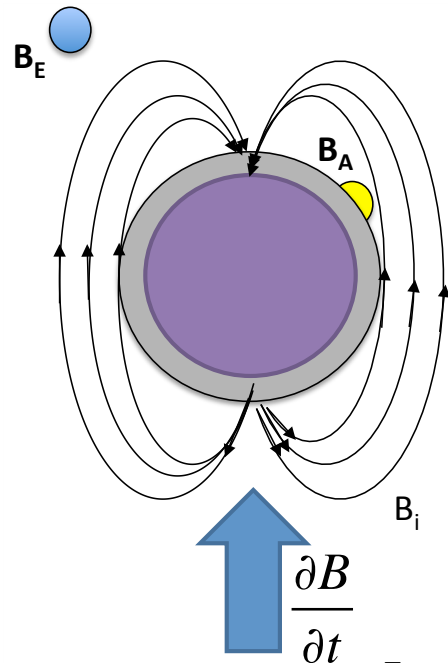Fuqua Haviland et al., 2019

The Apollo Picture

Time Domain EM (TDEM) Sounding Vacuum Model

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

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

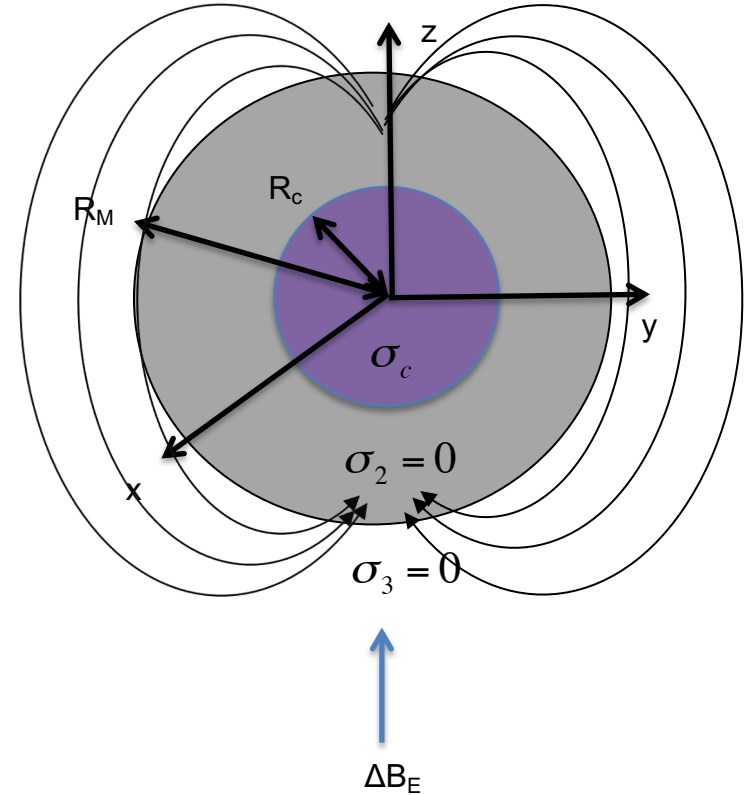$$F(t) \propto \exp\left(-t / \sigma_a a^2\right)$$

Dyal & Parkin, 1971

Fuqua Haviland et al., 2019

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TDEM Sounding Vacuum Model

Dyal & Parkin, 1971:

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

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

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

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

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

$$\mu_o \frac{\partial}{\partial r}\left(rA_0\right) = \mu_o \frac{\partial}{\partial r}\left(rA_{1=core}\right)$$
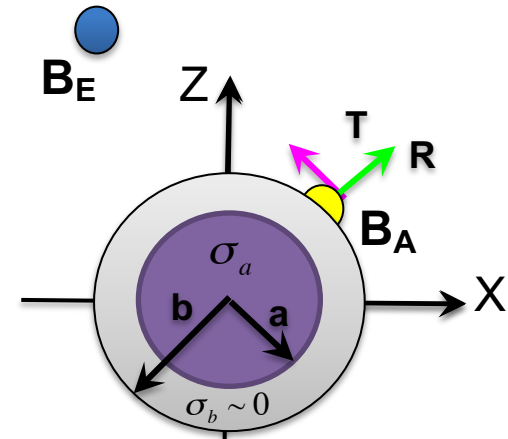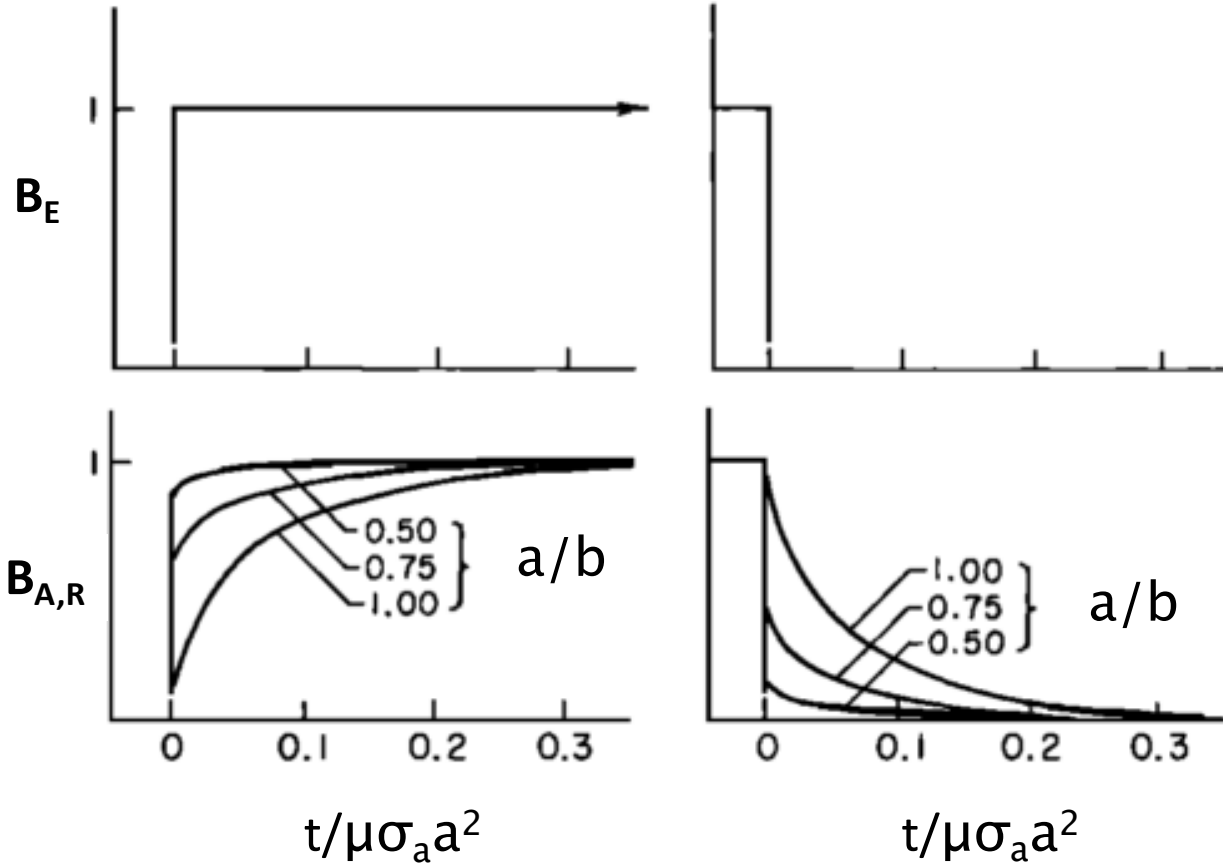
$$B_{\perp 0} = B_{\perp 1}$$

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

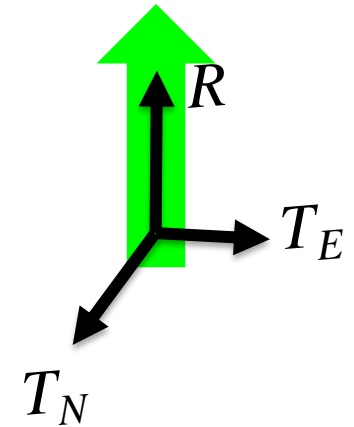B_E = External Driving Field (Reference Probe)

TDEM Sounding Theory

SWITCH ON

SWITCH OFF

B_E

$B_{A,R}$

0.50
0.75
1.00
a/b

1.00
0.75
0.50
a/b

0   0.1   0.2   0.3

0   0.1   0.2   0.3

$t/\mu\sigma_a a^2$

$t/\mu\sigma_a a^2$

B_E

Z

T   R

σ_a
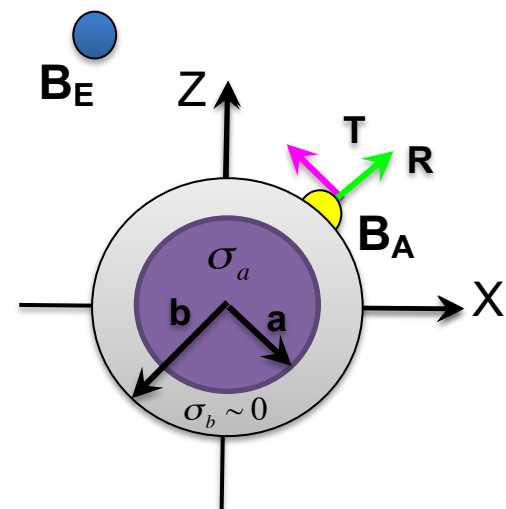
b   a
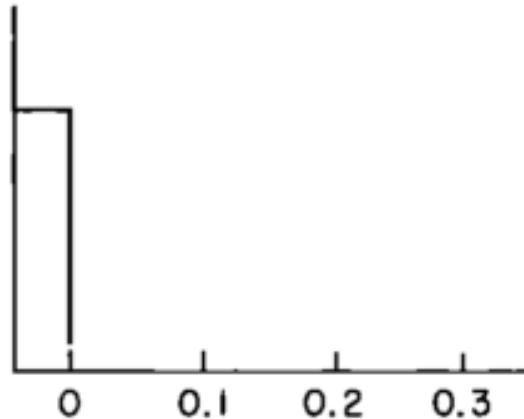
B_A

X

$\sigma_b \sim 0$

Fuqua Haviland et al., 2019

R

T_E

T_N

Dyal & Parkin 1971

Sonett, 1982

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TDEM Sounding Theory

SWITCH ON

SWITCH OFF

B_E

0   0.1   0.2   0.3

0   0.1   0.2   0.3

$t/\mu\sigma_a a^2$

$B_{A,T}$

$\frac{3}{2}$

1.00
0.75   a/b
0.50

1

$t/\mu\sigma_a a^2$

0.50
0.75   a/b
1.00

B_E

Z

T   R

σ_a

B_A

b   a

X

$\sigma_b \sim 0$

Fuqua Haviland et al., 2019

R

T_E

T_N

Dyal & Parkin 1971
Sonett, 1982

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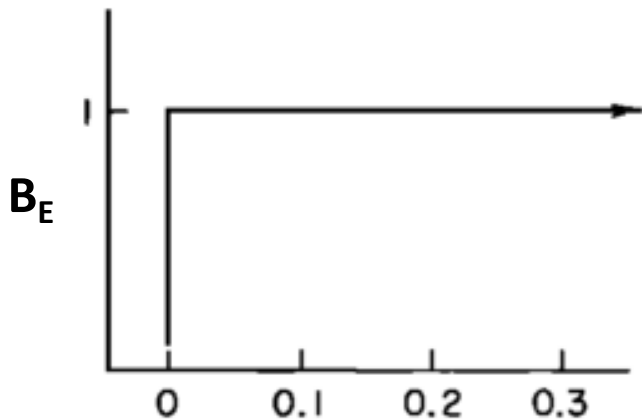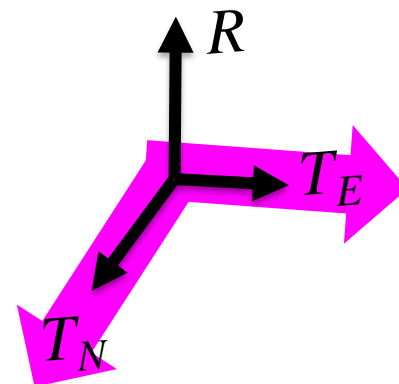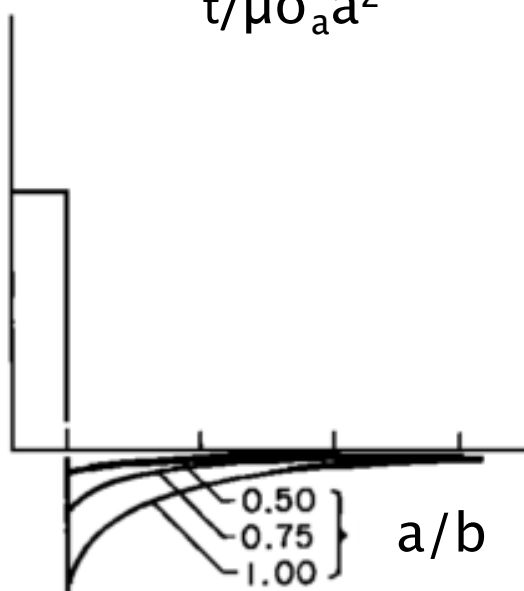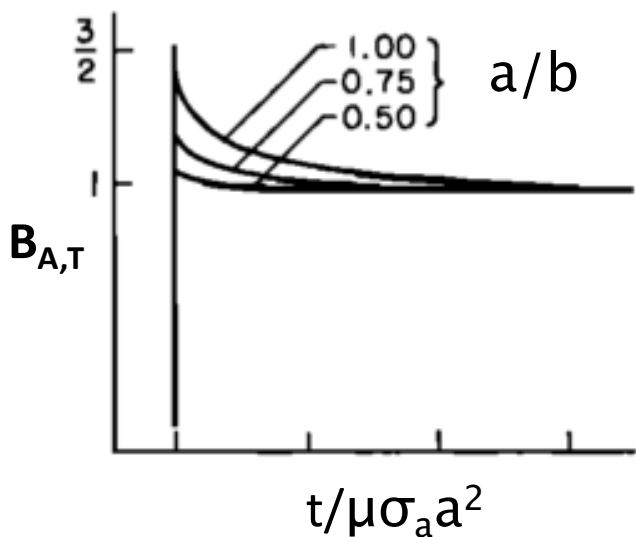
COMSOL Finite Element Method (FEM) Implementation

B$_A$ **Total Field (Surface Probe)**

Boundary Conditions

Ext. Driving Field
B$_E$ **(Ref Probe)**

COMSOL Moon Model

Misfit   **<1**

>1

$$\nabla^2 B = \sigma \frac{\partial B}{\partial t}$$

B$_E$

B$_A$

σ

σ
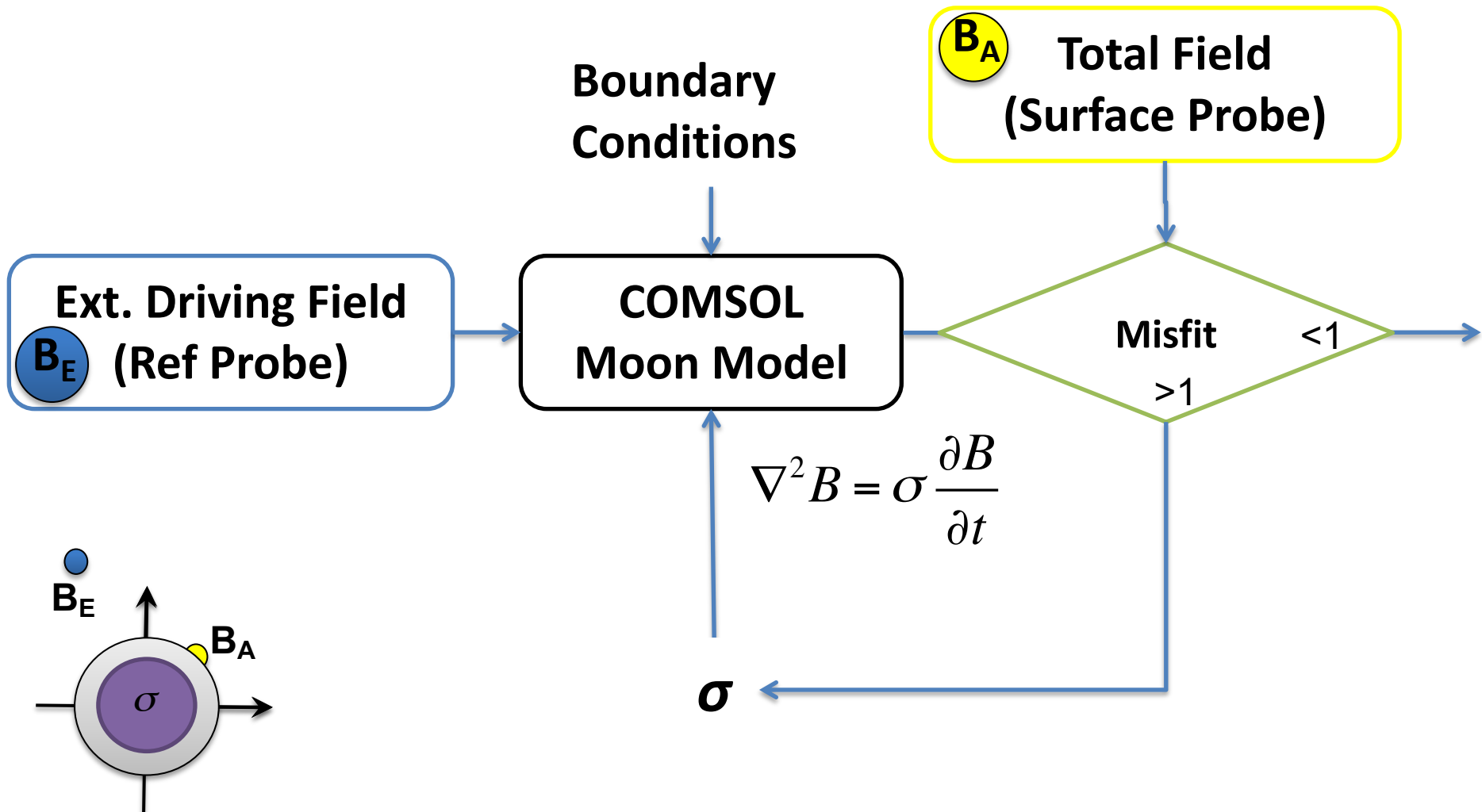
COMSOL FEM Forward Model

NASA/Marshall Space Flight Center
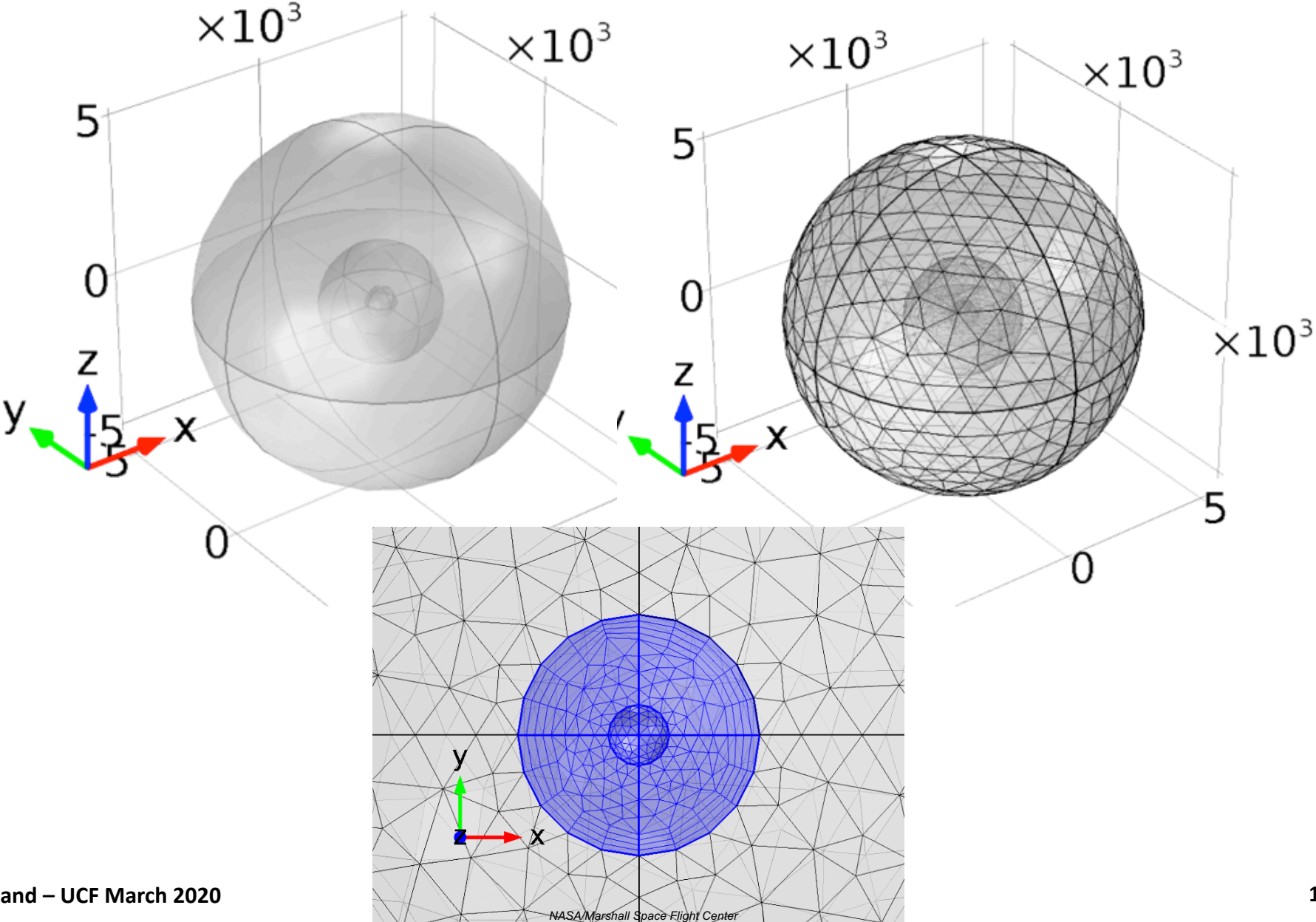
3D Electrical Conductivity Models

$\sigma_{vacuum} = 1e\text{-}13$ S/m

$\sigma_{crust} = 1e\text{-}9$ S/m

$\sigma_{mantle} = 1e\text{-}4$ S/m

$\sigma_{core} = 1e\text{-}2$ S/m
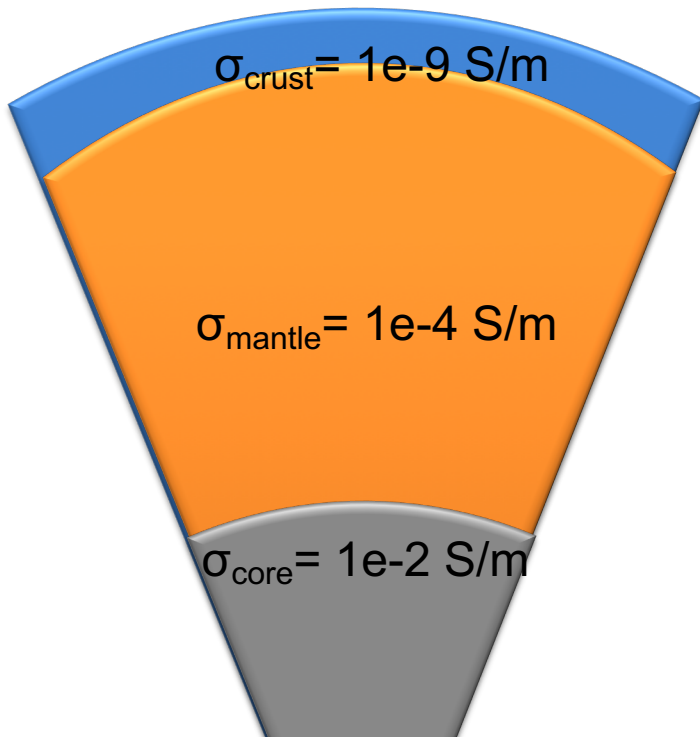
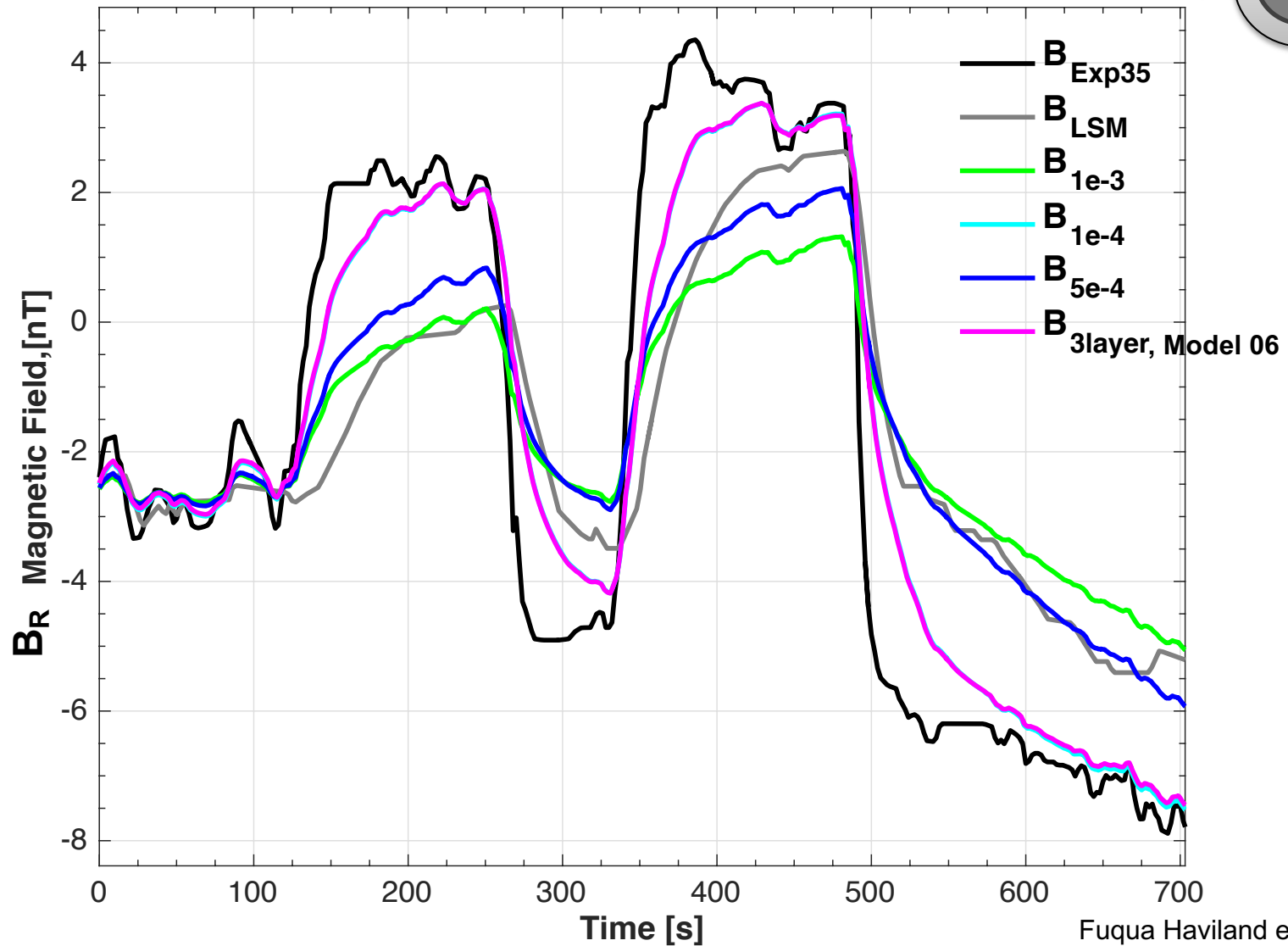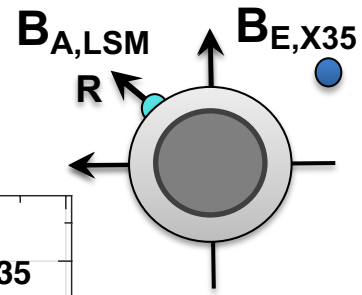$\sigma_{vacuum} = 1e\text{-}13$ S/m

$\sigma = 1e\text{-}4(r/R_m)$ S/m
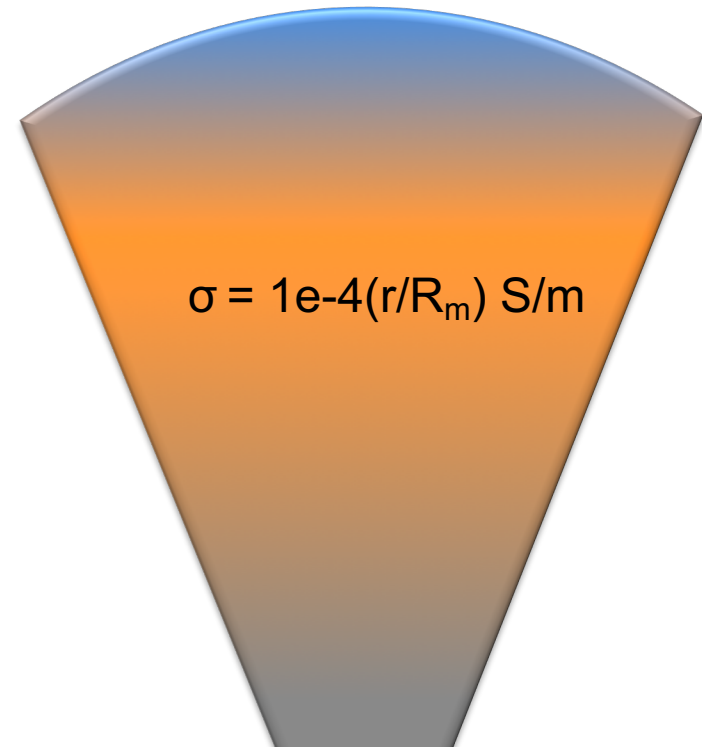
FEM enables three-dimensional electrical conductivity profiles.

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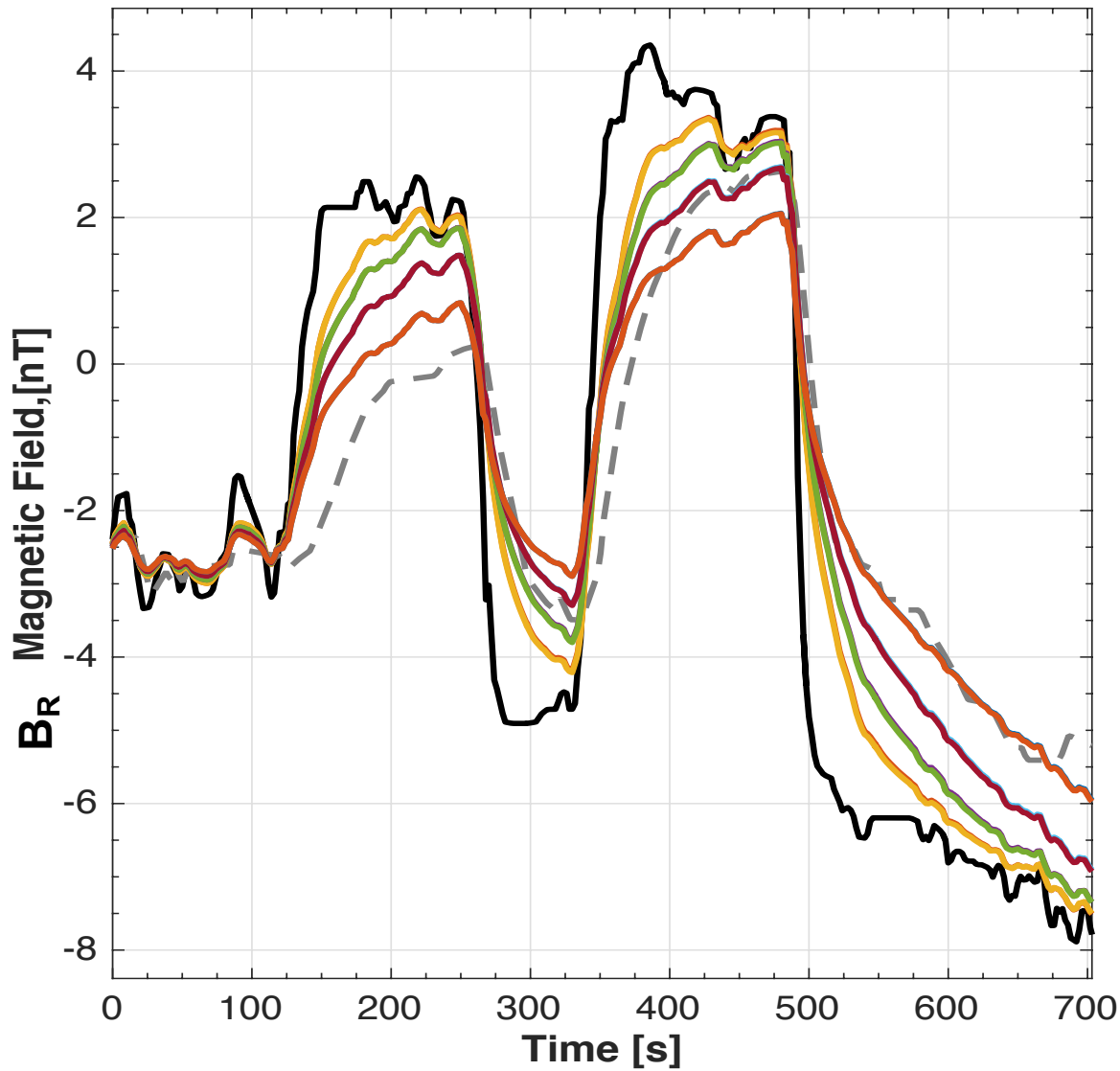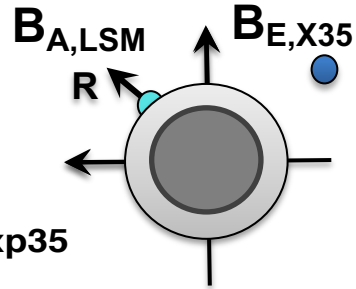
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Apollo Event

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

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Apollo Event

Legend:
- B_{Exp35}
- B_{LSM} (dashed)
- $B_{06:m.1.0e-4,c.1e-2}$
- $B_{07:m.1.0e-4,c.1e+3}$
- $B_{08:m.1.5e-4,c.1e-2}$
- $B_{09:m.1.5e-4,c.1e+3}$
- $B_{10:m.2.5e-4,c.1e-2}$
- $B_{11:m.2.5e-4,c.1e+3}$
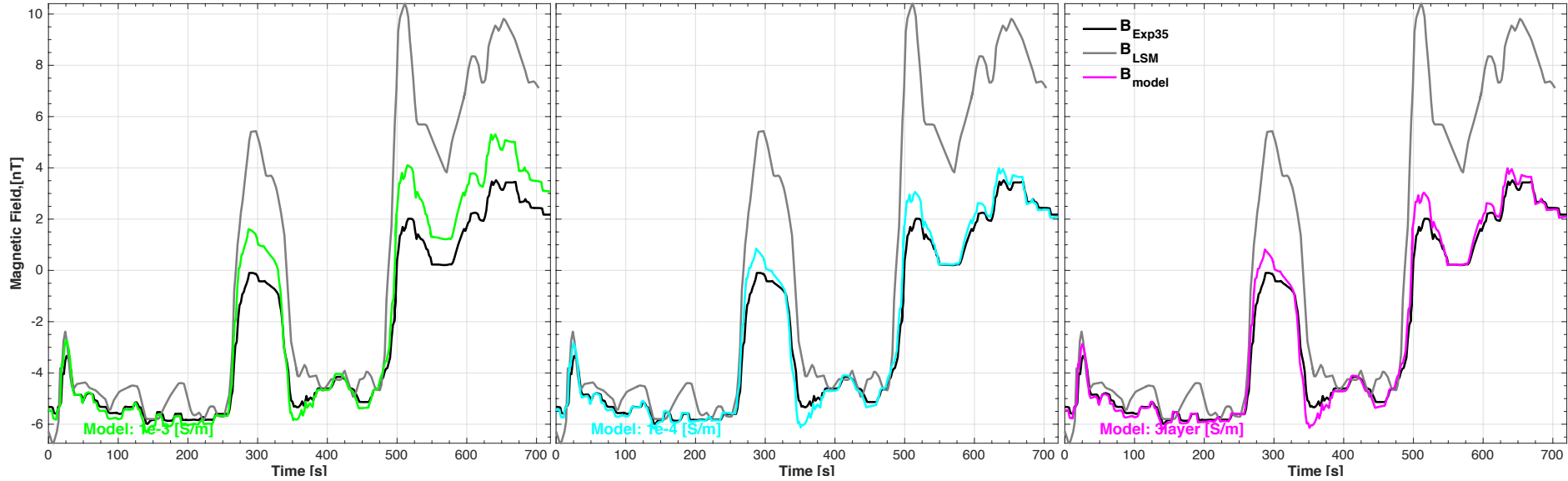- $B_{12:m.5.0e-4,c.1e-2}$
- $B_{13:m.5.0e-4,c.1e+3}$

$B_{A,LSM}$ $B_{E,X35}$ R

Axis labels: B_R Magnetic Field, [nT] (y-axis); Time [s] (x-axis)

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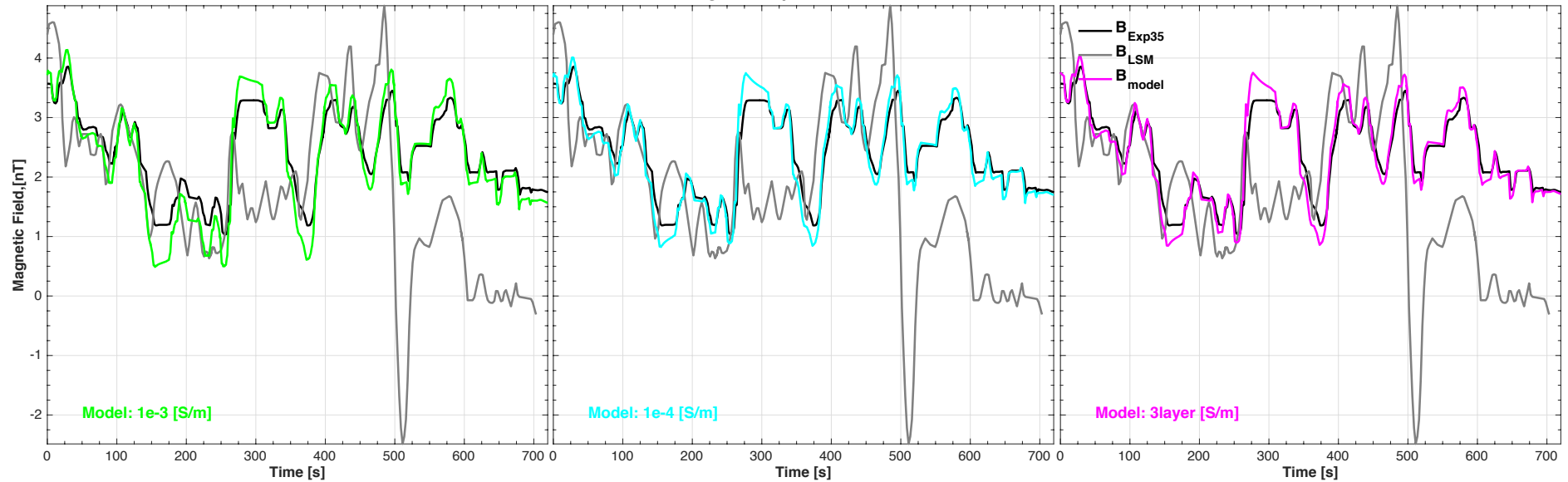After Dyal et al. [1971] figure 10

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Apollo Event

Digitized Apollo Data: North

Digitized Apollo Data: East

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

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Wake Current Systems
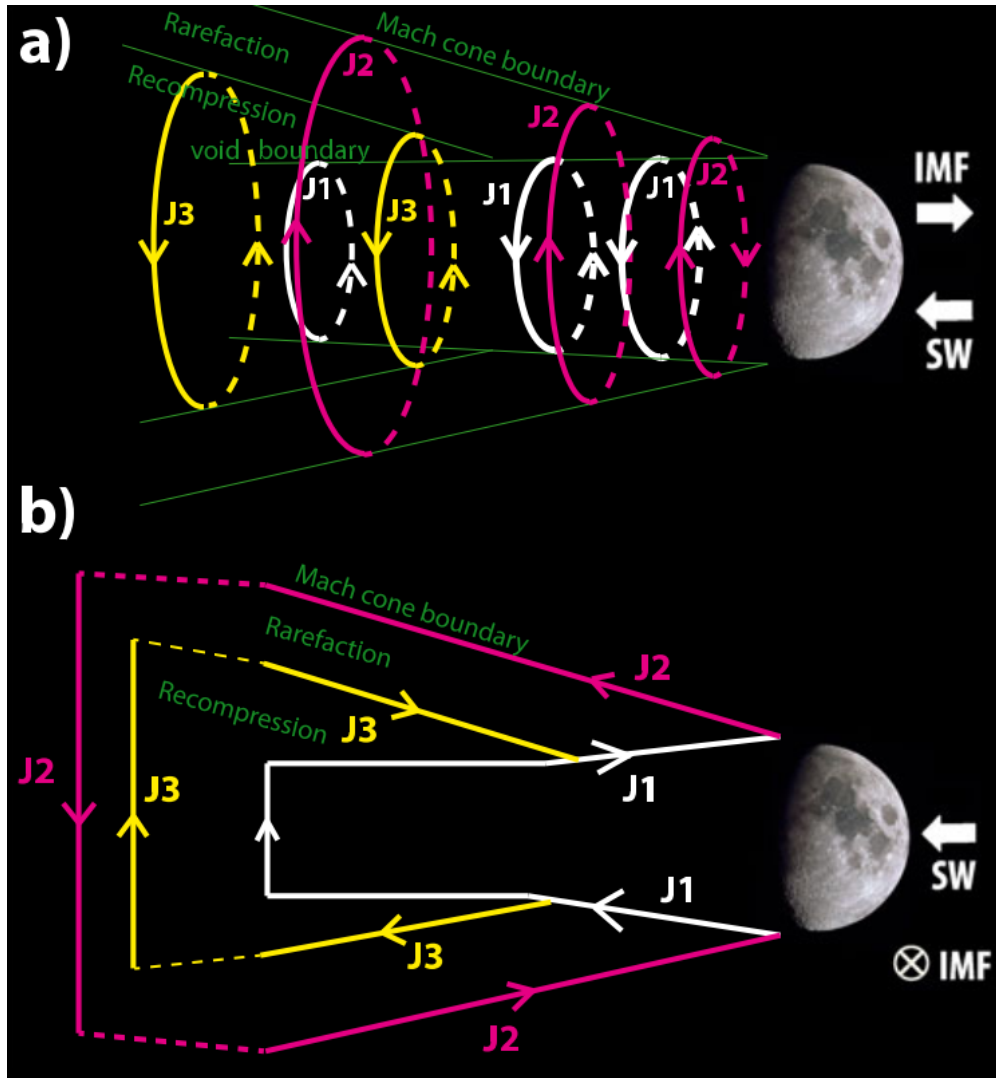
what we know:
- *wake forms on nightside due to dayside absorption and vacuum cavity*
- *wake current systems (incl. structure, extent) organize according to solar wind characteristics*

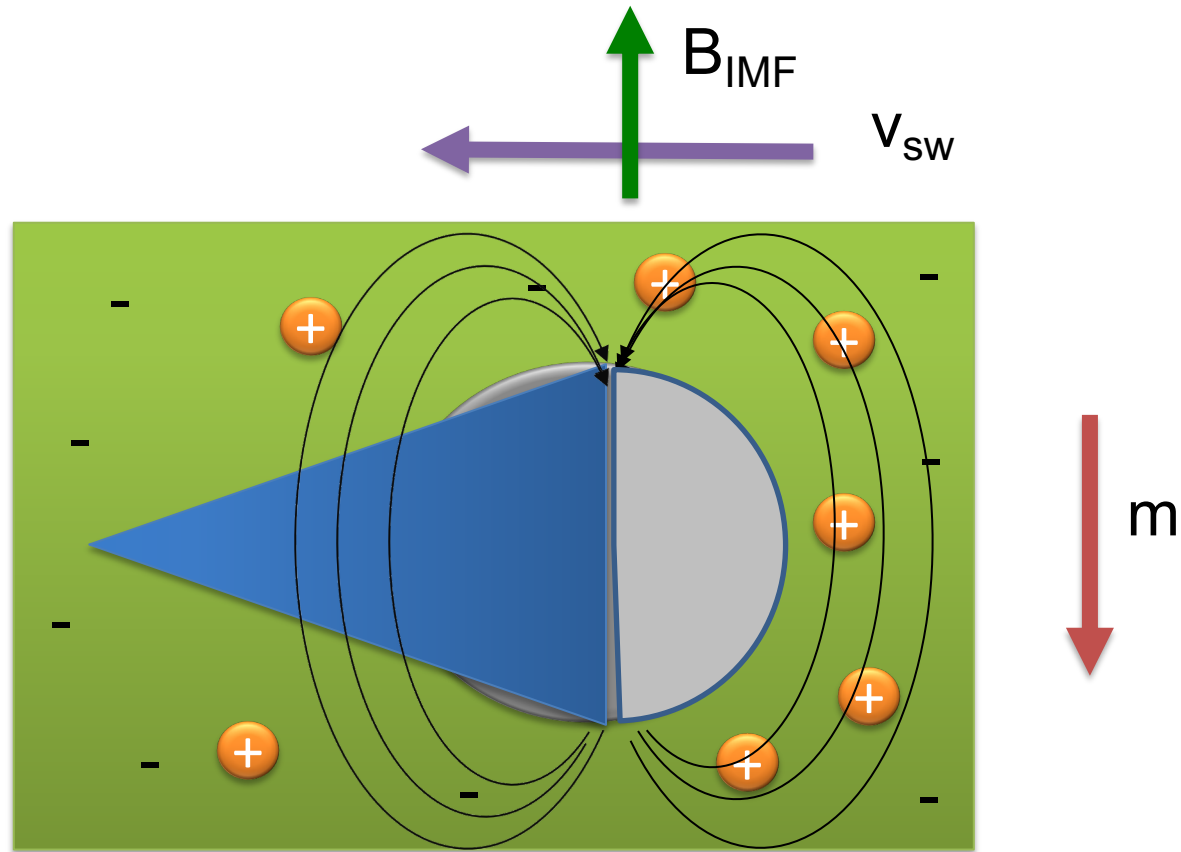$$\boldsymbol{v}_{sw},\ \boldsymbol{B}_{IMF}$$
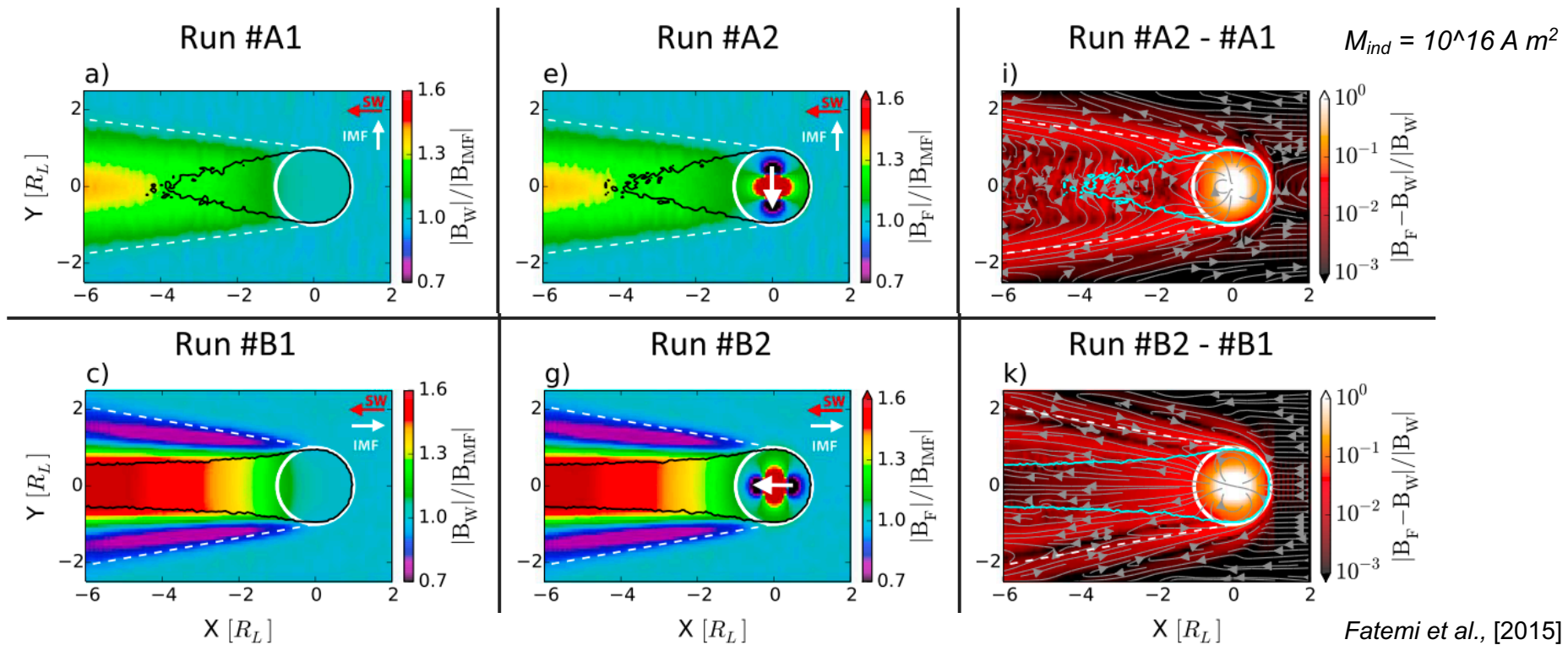$$n_e,\ n_i$$
$$T_e,\ T_i$$
$$\sigma(r), t \quad \textit{This study}$$

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

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Static Plasma Hybrid Kinetic Model

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Static Hybrid Model Results

Fatemi et al., [2015]
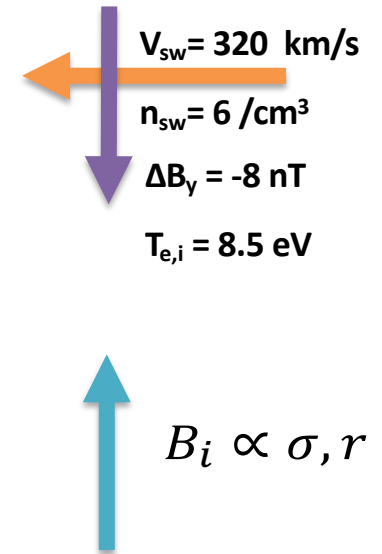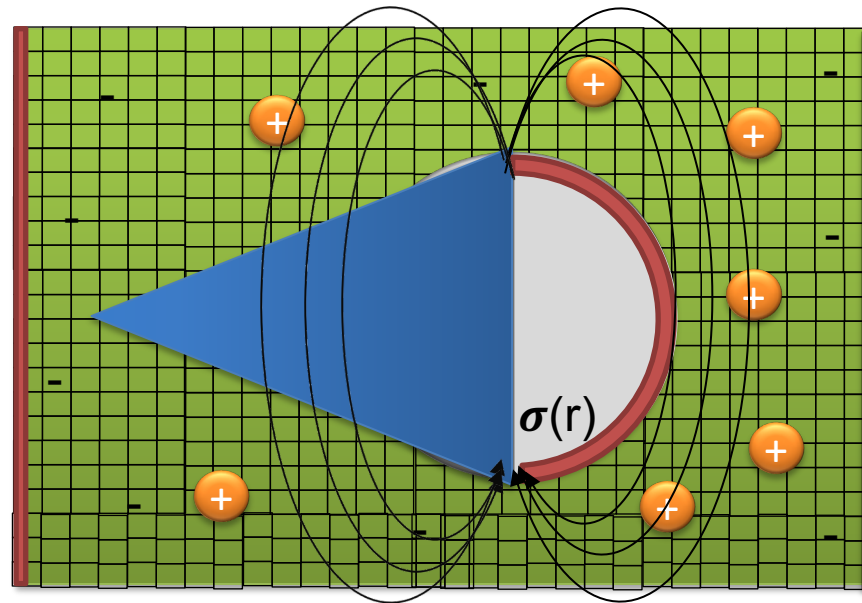
Dayside confinement, as predicted. Nightside fields are not confined within wake cavity. Strong induced field signatures in the deep wake near surface, especially with large IMF changes.

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Transient Plasma Hybrid Kinetic Induction Model

General Case, Perpendicular

$V_{sw} = 320$ km/s

$n_{sw} = 6$ /cm^3

$\Delta B_y = -8$ nT

$T_{e,i} = 8.5$ eV

$\sigma(r)$

$B_i \propto \sigma, r$

- Cell size: 50 km (~0.028 R_L)
- 16 macroparticles (only protons) per cell
- $t_{step} = 0.001$ s
- $0 < t < \sim300$ s, t=24 s IMF discontinuity
- $\sigma_1 = 1.0\,e-8,\ 1.0\,e-4,\ 1.0\,e-3$ [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

(a)

$\sigma = 1.0e\text{-}8$ S/m, t = 50 sec

B_x | B_y | B_z | $|B|$ | [nT]

Direction of disturbance

V_{sw}= 320 km/s

n_{sw}= 6 /cm³

ΔB_y = -8 nT

t = 50 s

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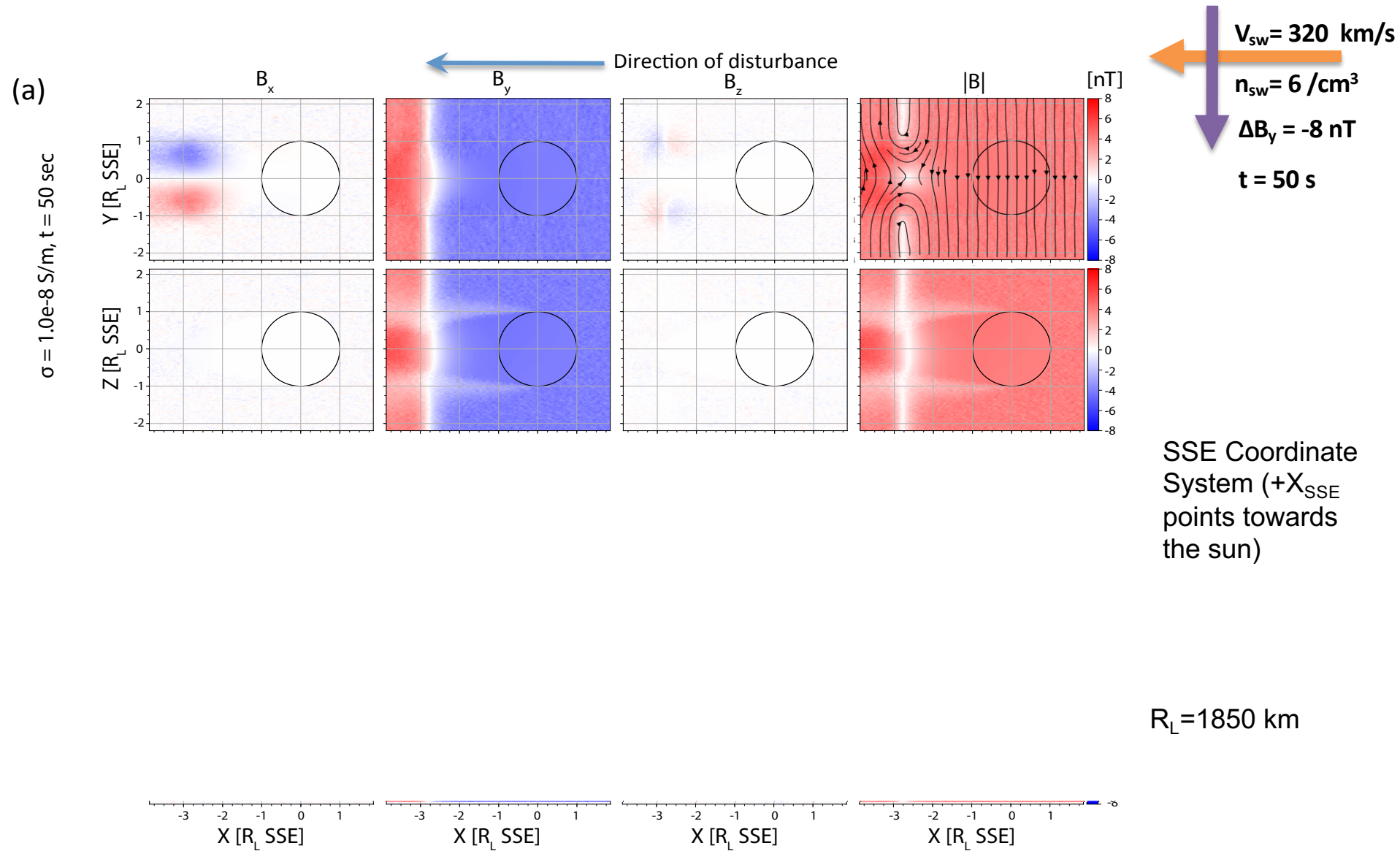
R_L=1850 km

Results: Single Time Step (con't)

(c)

Difference, t = 50 sec

Direction of disturbance

B_x B_y B_z $|B|$ [nT]

Y [R_L SSE]

Z [R_L SSE]

X [R_L SSE]   X [R_L SSE]   X [R_L SSE]   X [R_L SSE]

V_{sw} = 320 km/s

n_{sw} = 6 /cm³

ΔB_y = -8 nT

t = 50 s
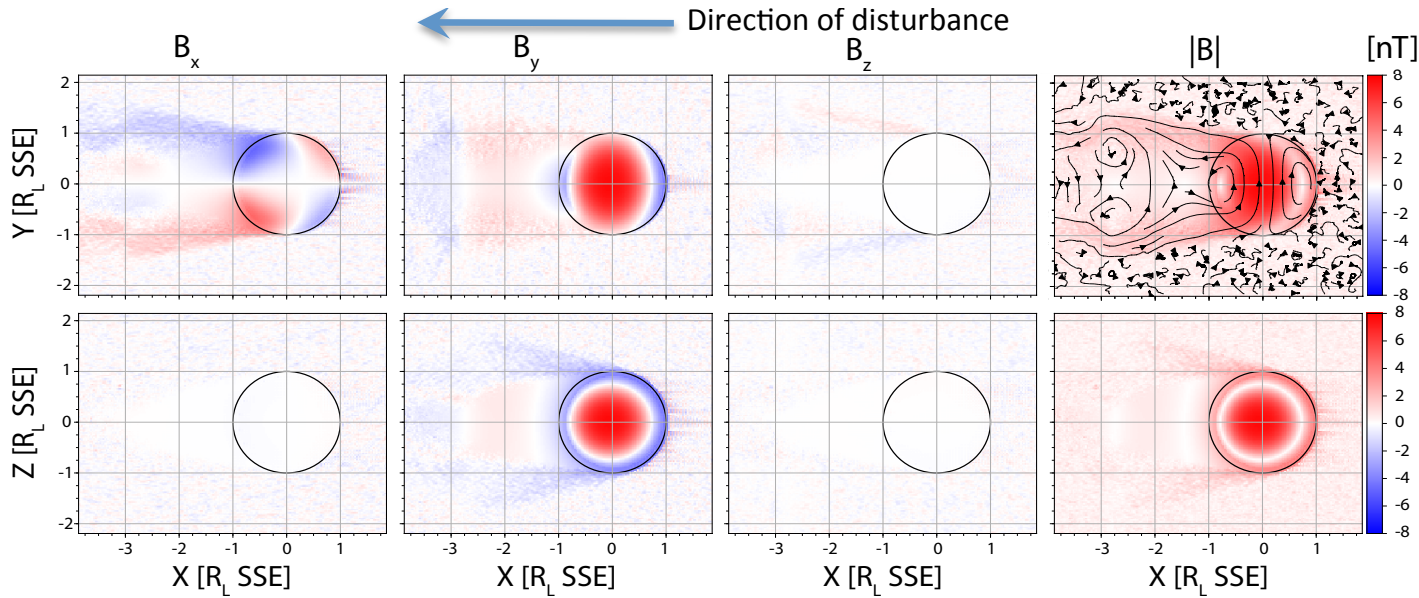
Residual Difference = Conductive Case − Resistive Case

(Plasma Effects Only)

Results: Time Dependence

$V_{sw} = 320$ km/s

$n_{sw} = 6$ /cm³

$\Delta B_y = -8$ nT

| B_y, t = 20 sec | B_y, t = 30 sec | B_y, t = 35 sec | B_y, t = 50 sec | B_y, t = 80 sec | B_y, t = 220 sec | [nT] |

$\sigma = 1.0e-8$ S/m

Y [R_L SSE]

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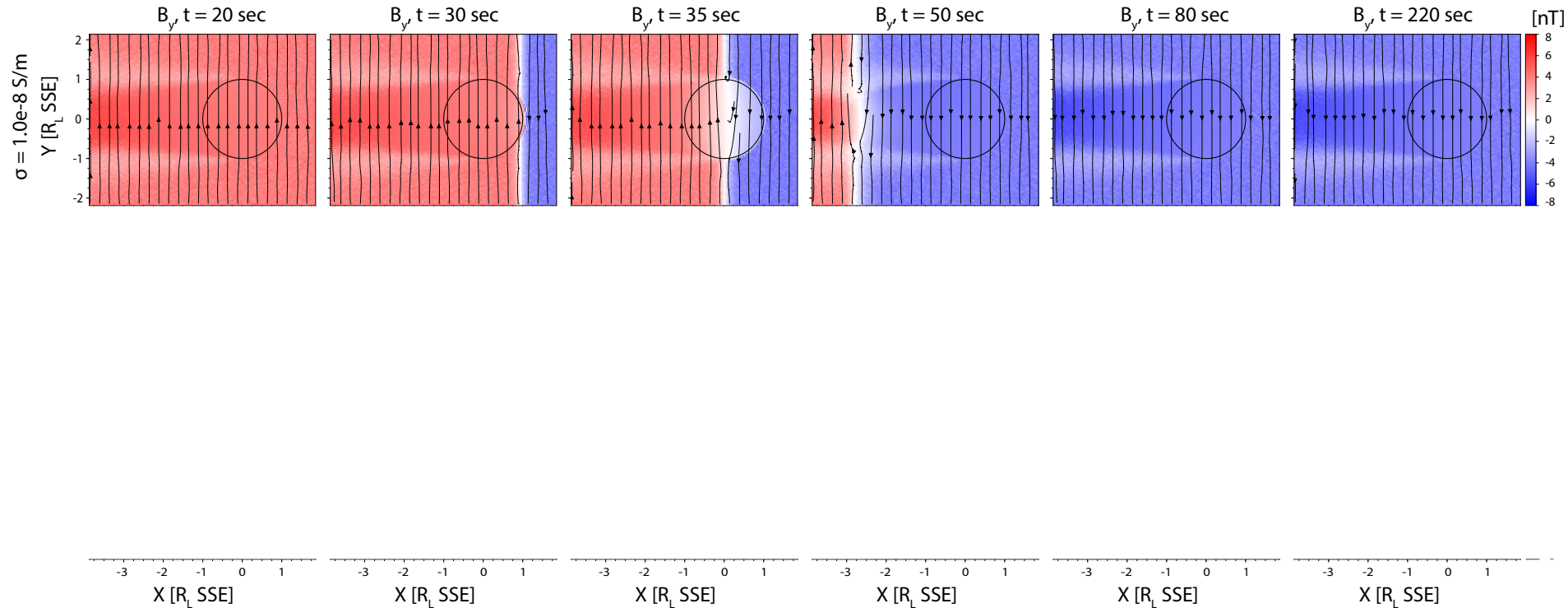
SSE Coordinate System (+X_{SSE} points towards the sun)
R_L =1850 km

Results: Case Study 1 Time Series

Observer 1, Full Fields

Key
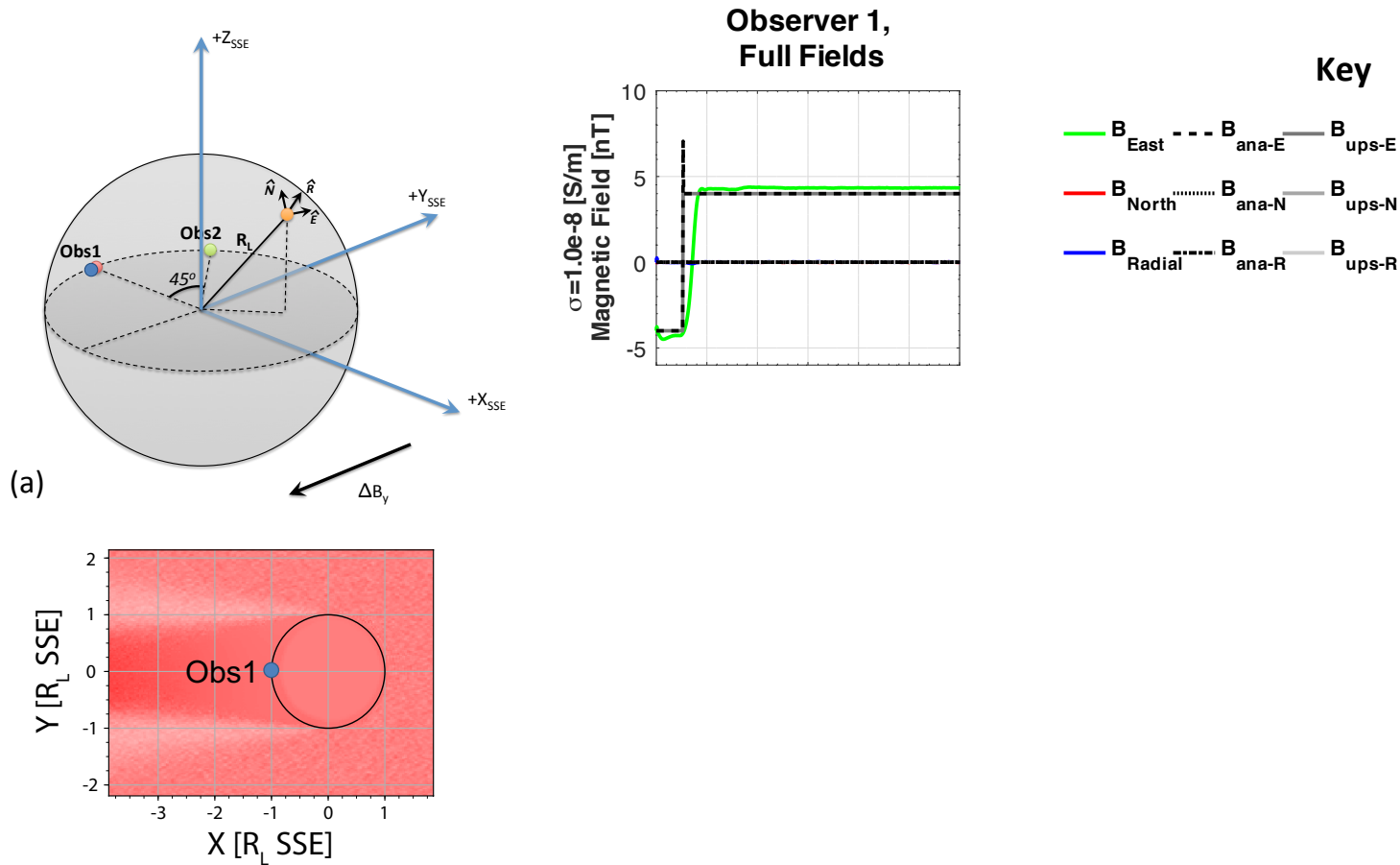
Results: Case Study 2 Time Series
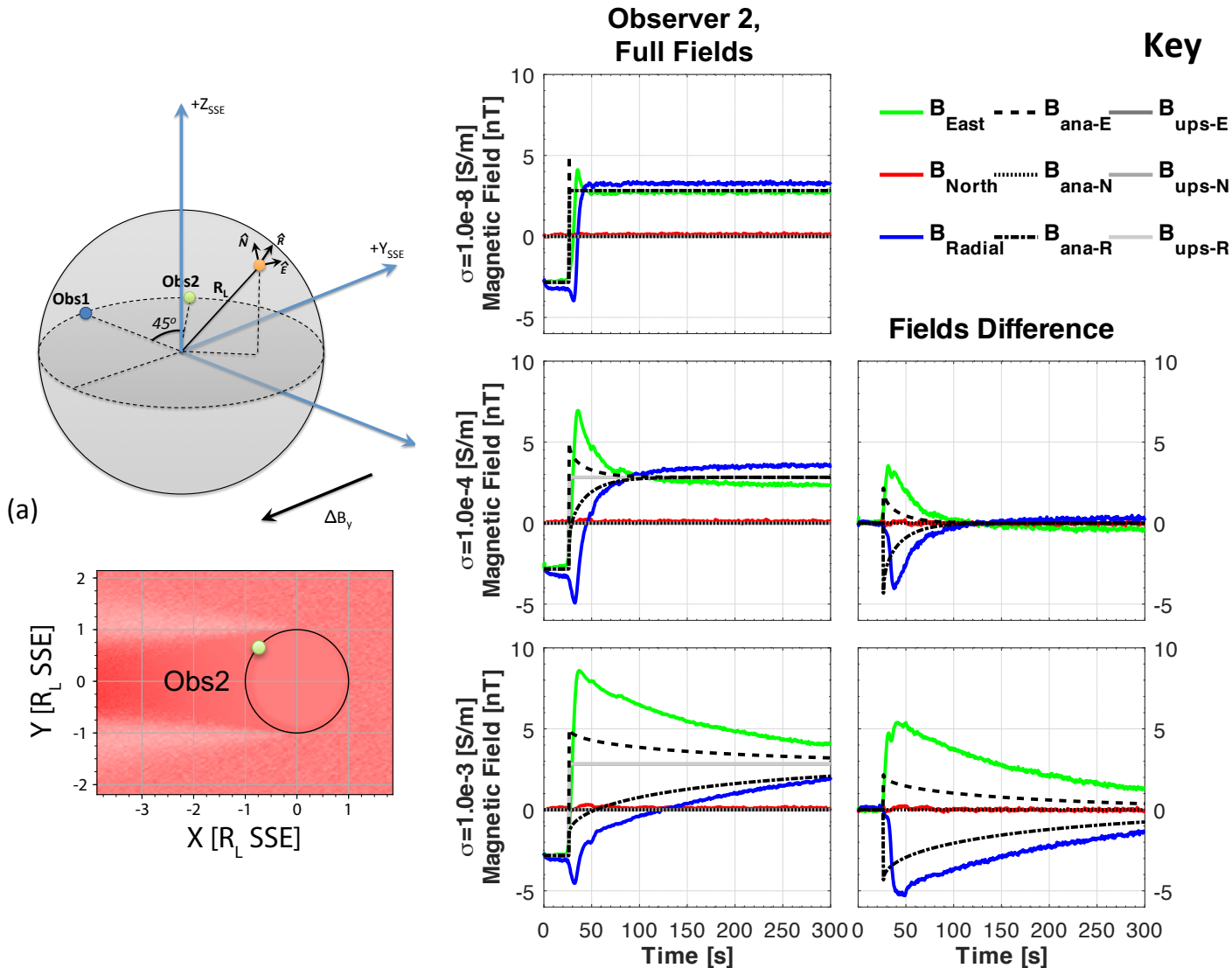
Observer 2, Full Fields

Key

Fields Difference

(a)

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Fuqua Haviland et al., 2019. GRL.

Lunar Electromagnetic (EM) Sounding Transient Response Method

(a) TDEM Geometry

B_E

$+Z_{SEL}$

T_n R

B_A

σ_1

$+X_{SEL}$

b a

$\sigma_2 \ll 1$

(b) Magnetotail Induction

B_E

B_A

B_i

$$\frac{\partial B}{\partial t}$$

(c) Solar Wind Induction

B_E

$+Z_{SSE}$

$+X_{SSE}$

B_A

B_i

$$\frac{\partial B}{\partial t}$$

Fuqua Haviland et al., 2019. ASR

The Apollo Picture
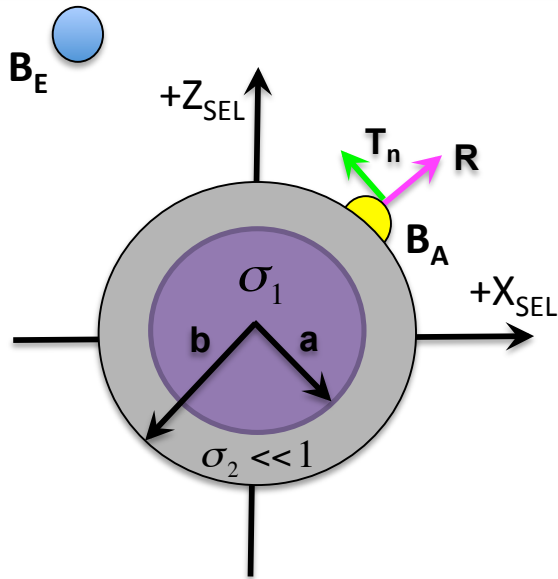
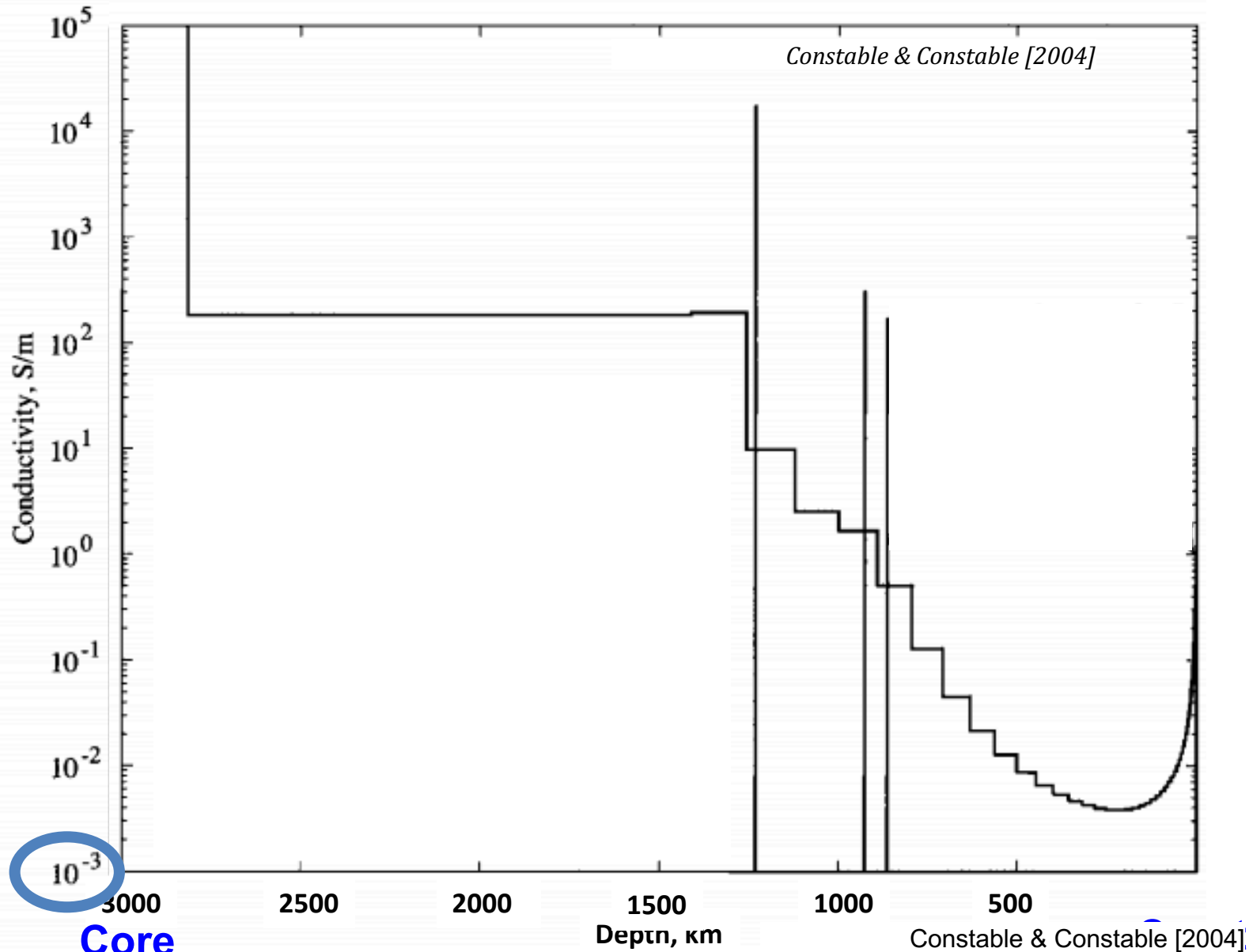# Electrical Conductivity Profile
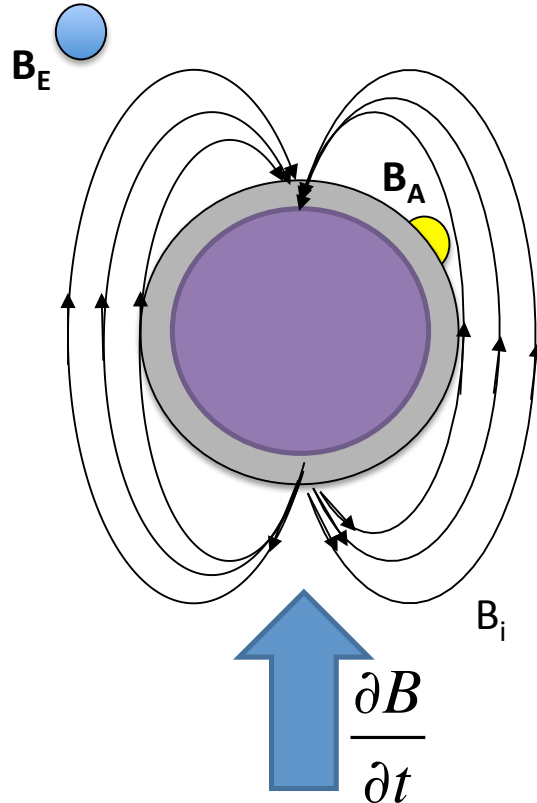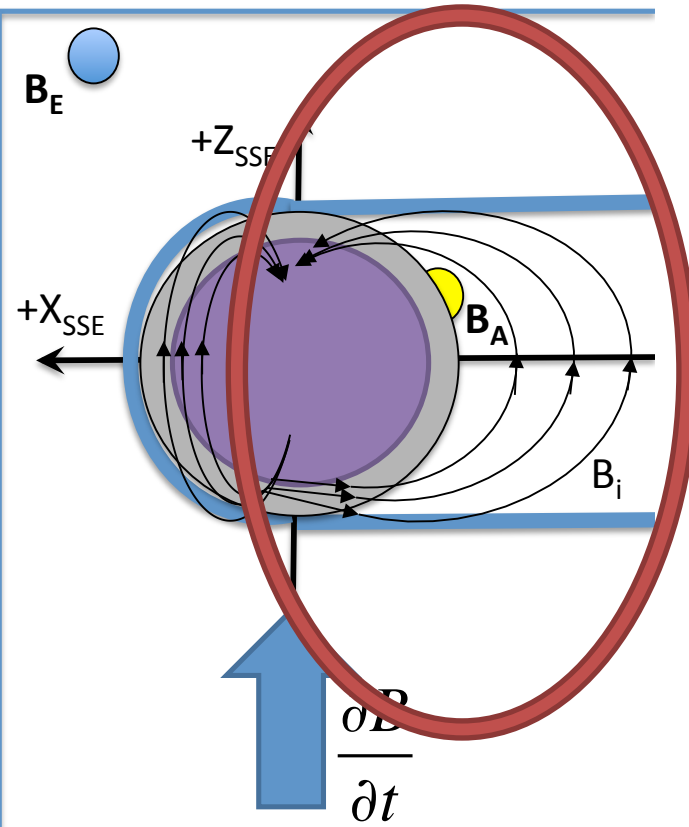
Lunar Electrical Conductivity Profile
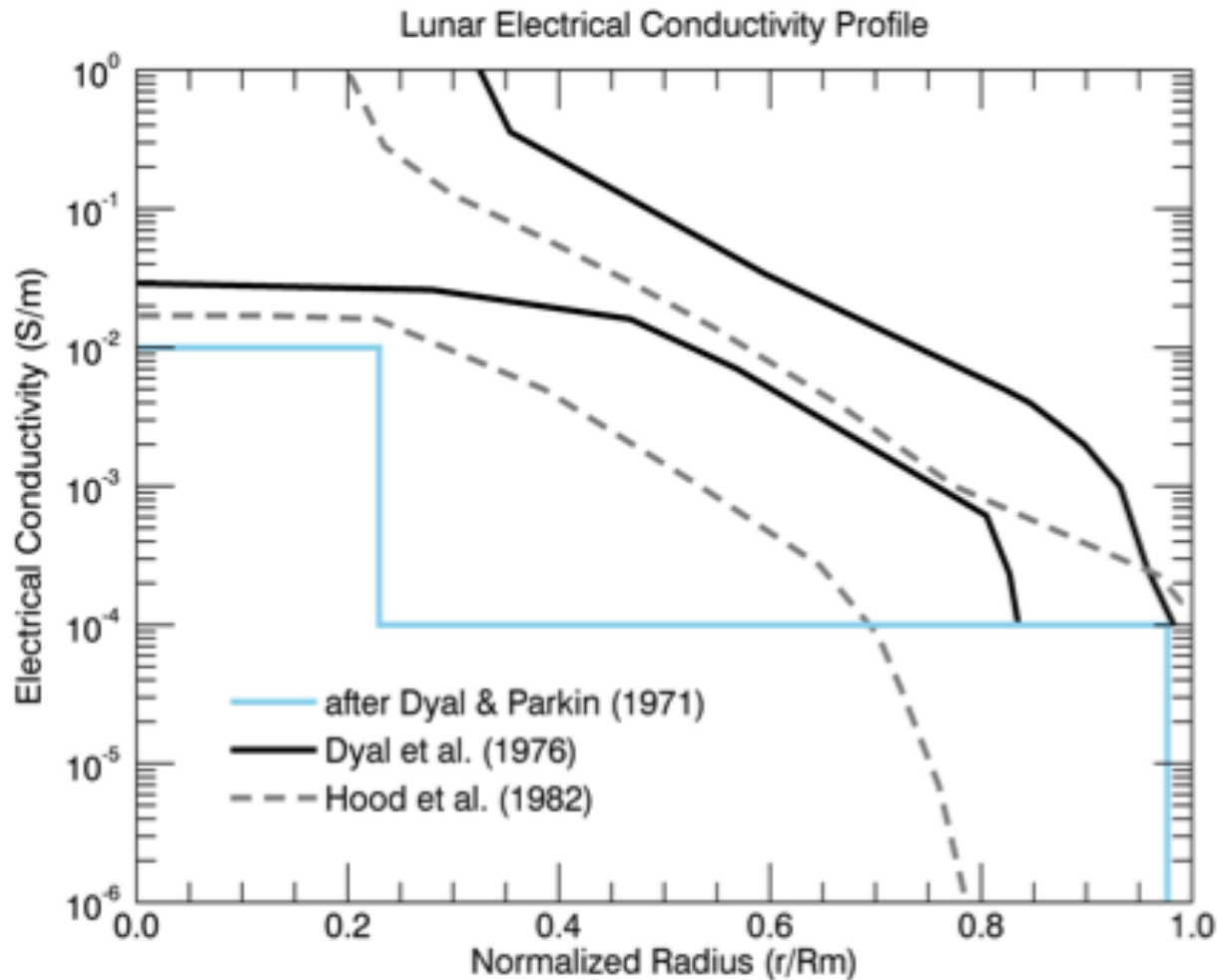
Fuqua Haviland et al., 2019. ASR.

Elec. Conductivity Profile - Earth

Constable & Constable [2004]

Constable & Constable [2004]

Core

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.

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Lunar Deep Space Gateway
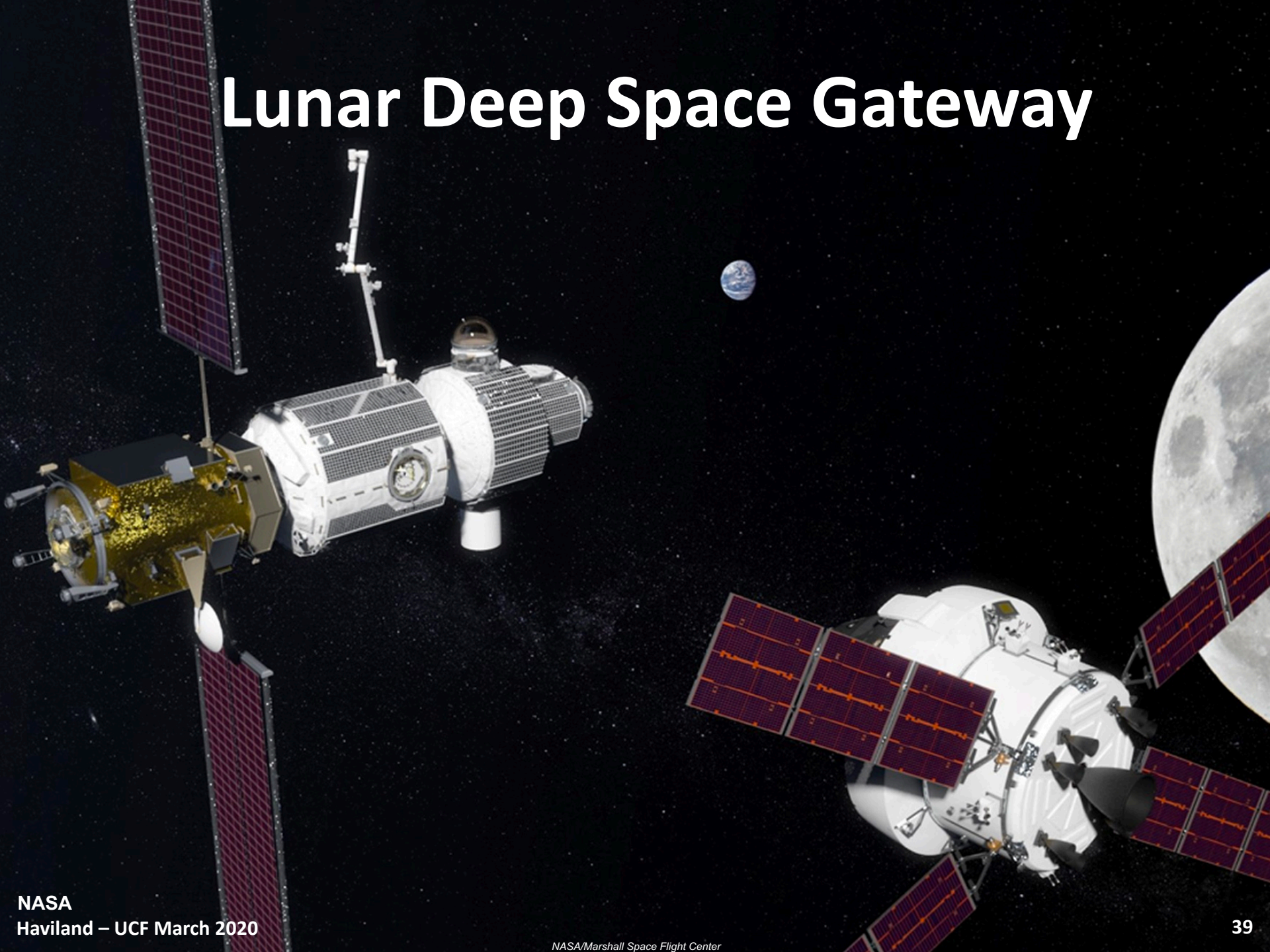
Commercial Lunar Payload Services (CPLS)

NASA

*NASA/Marshall Space Flight Center*
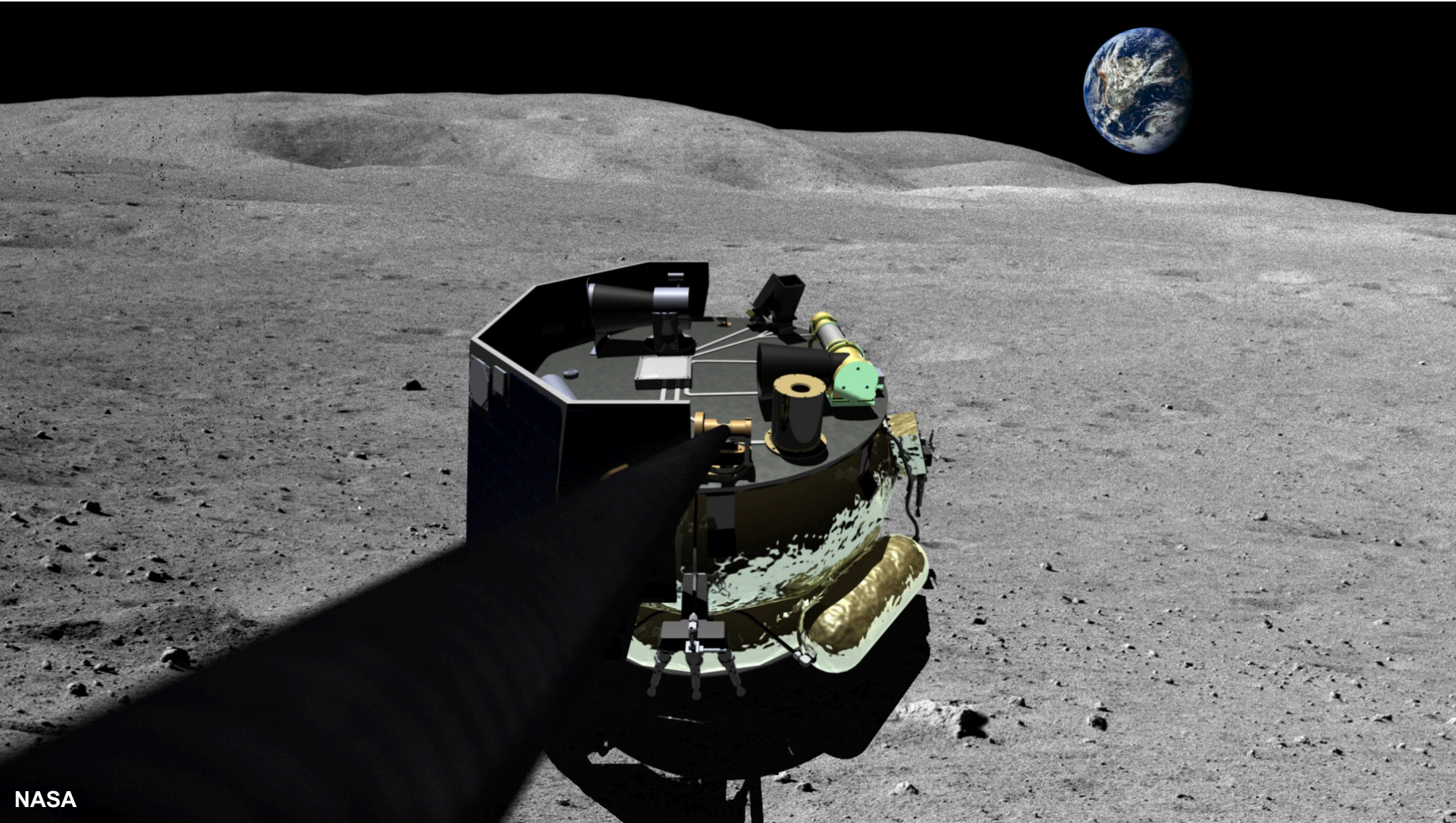
Lunar Geophysical Network (LGN)

Mission Objectives: to improve the state of knowledge of the lunar interior in terms of composition, structure, temperature.
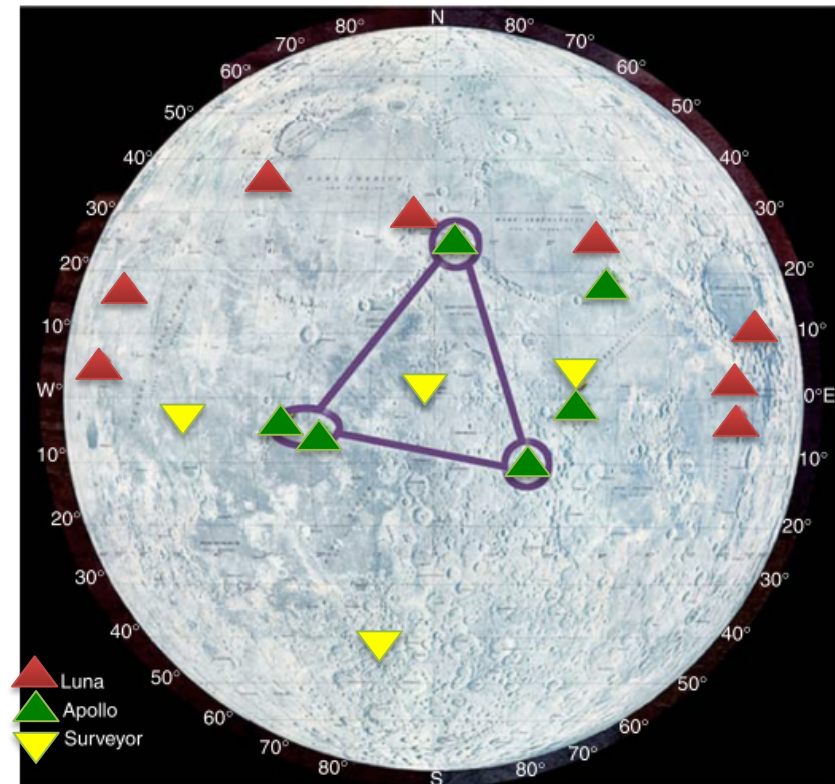
Project Description: The LGN will be composed of a network of ~4 stations with one farside station and communications orbiter. Each lander containing next generation instruments.

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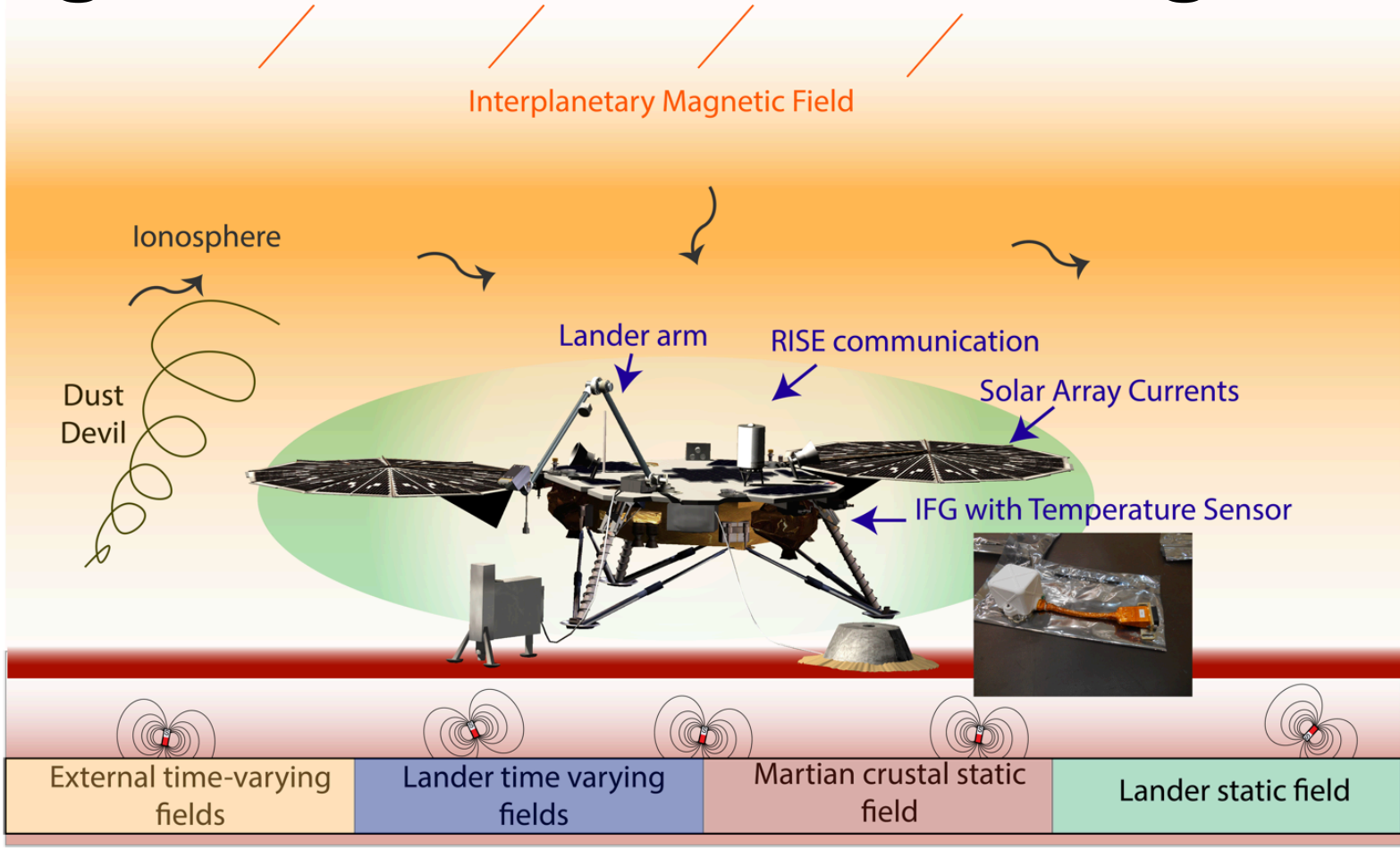

NASA
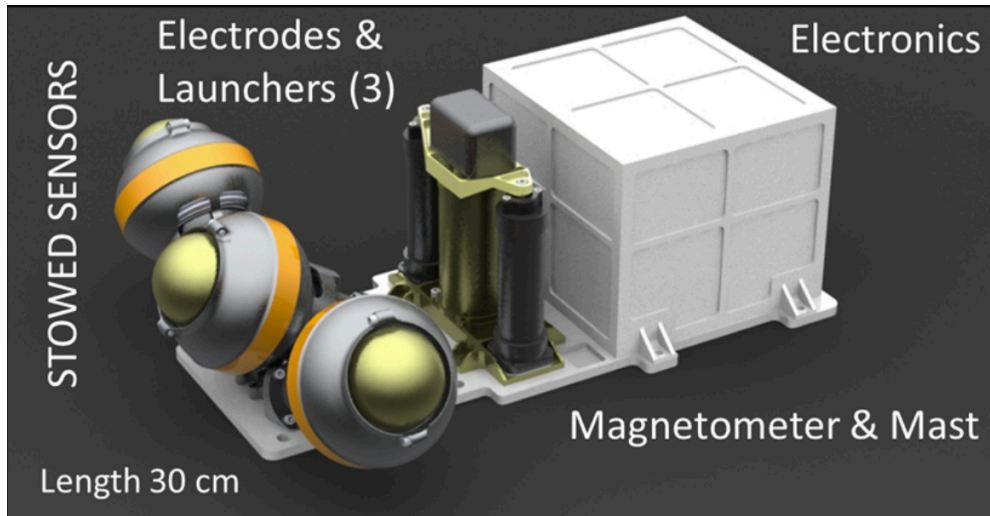
CPLS Lunar Magnetic Sounder, Grimm et al. 2020

Lognonné, 2007, 10.03 Planetary Seismology, p. 73

InSight Potential EM Sounding at Mars

Interplanetary Magnetic Field

Ionosphere

Dust Devil

Lander arm

RISE communication

Solar Array Currents

IFG with Temperature Sensor

| External time-varying fields | Lander time varying fields | Martian crustal static field | Lander static field |

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).

# 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.

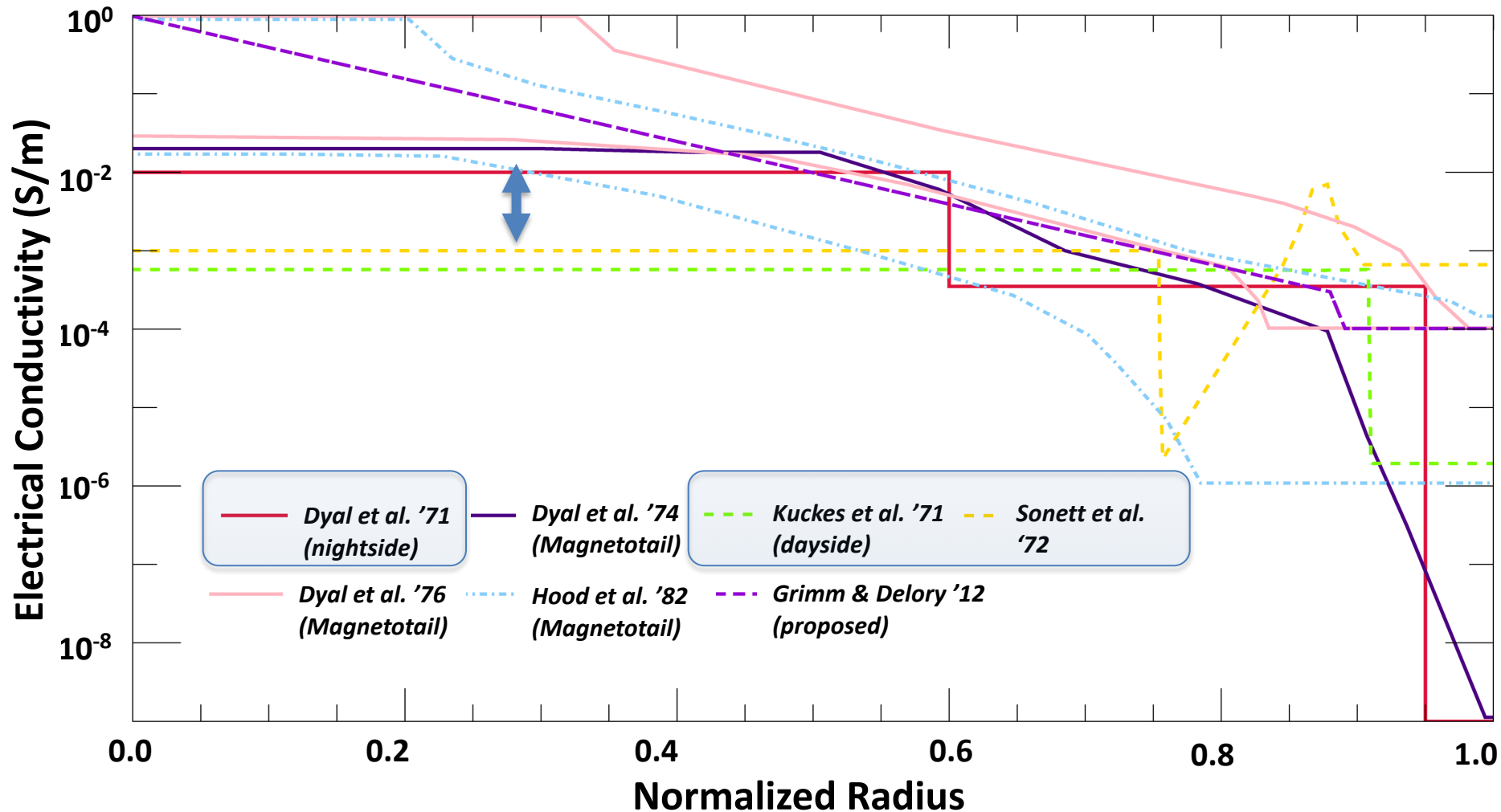**Funding:** Lunar Discovery and Exploration Program (LDEP)

~5"
~7"
~7"
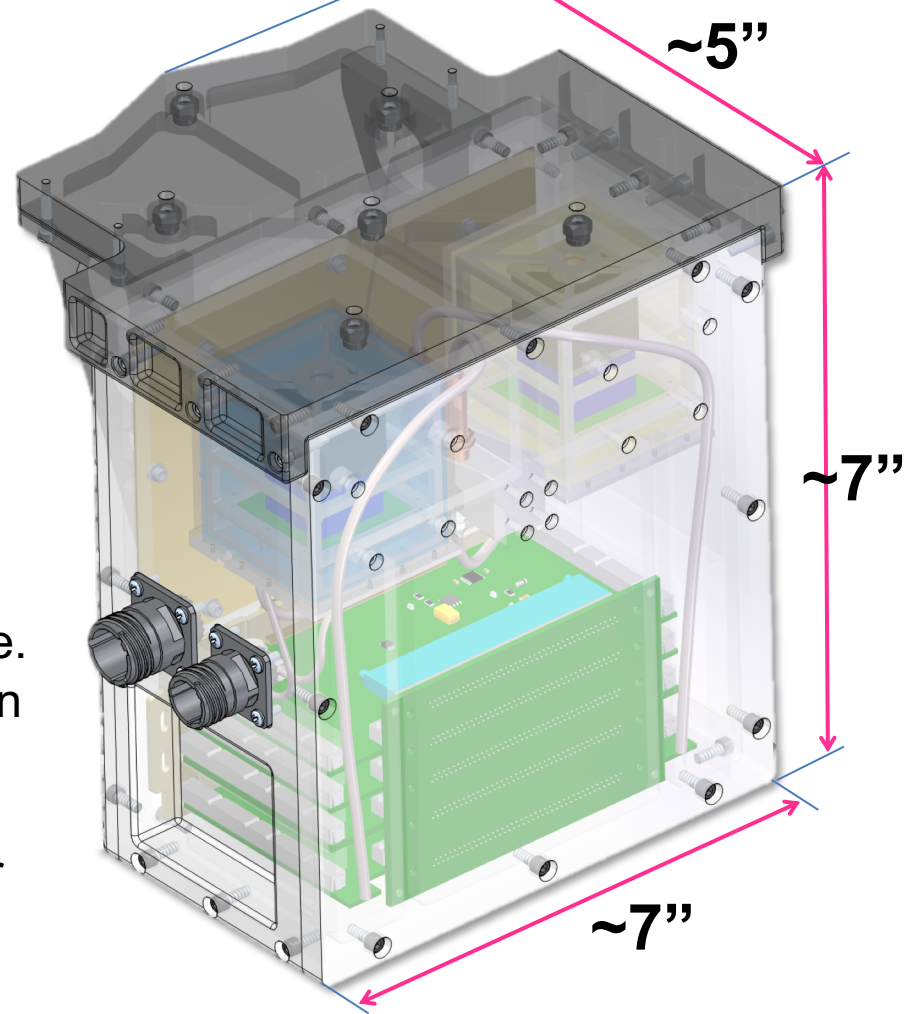
NMLS Mechanical Model

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

Questions?
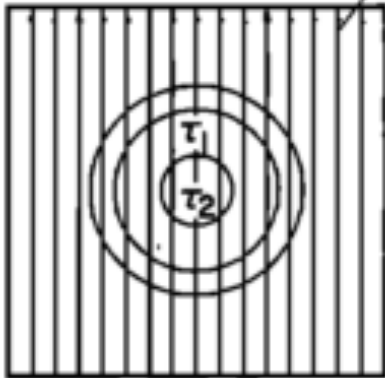
NASA/Marshall Space Flight Center

Summary of Apollo Lunar Electrical Conductivity Profiles

NASA/Marshall Space Flight Center

FIELD LINES

(a) t < 0
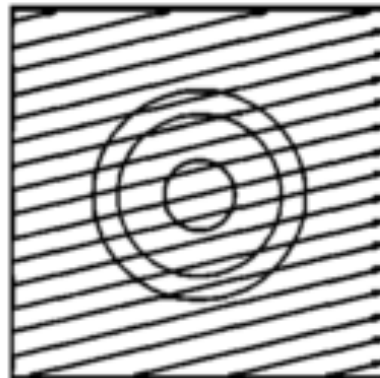
(b) 0 < t < τ_1 << t_2

(c) τ_1 < t < τ_2

(d) t >> τ_2