# Science Case for a Lander or Rover Mission to a Lunar Magnetic Anomaly and Swirl


David T. Blewett*

*Johns Hopkins University Applied Physics Lab*

Co-authors:
Jasper Halekas, University of Iowa
Dany Waller, Johns Hopkins University
Joshua Cahill, JHU-APL
Ariel Deutsch, Brown University/NASA-Ames
Timothy D. Glotch, Stony Brook University
Leonardo Regoli, JHU-APL
Sonia Tikoo, Stanford University
Sarah Vines, JHU-APL
Xu Wang, University of Colorado-LASP

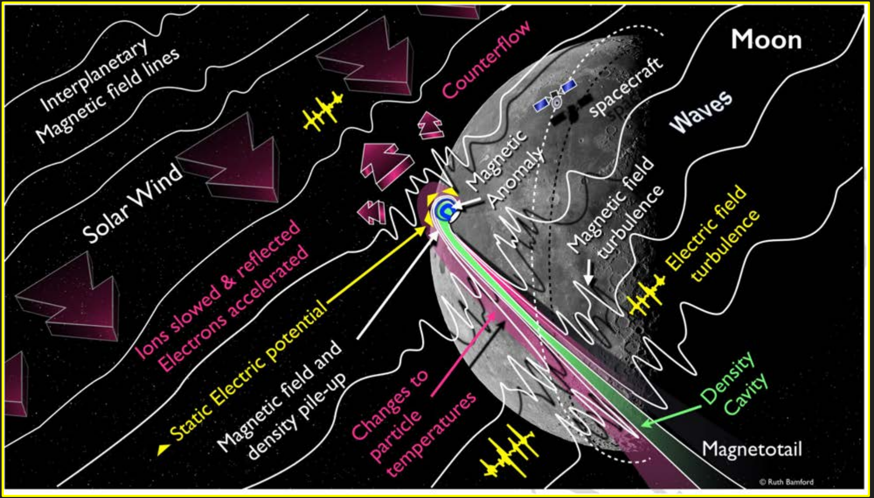

Presentation to the Planetary Decadal Survey
Panel on Mercury and the Moon
2021 Feb 26


*david.blewett@jhuapl.edu


JOHNS HOPKINS APPLIED PHYSICS LABORATORY

# Lunar Swirls and Lunar Magnetic Anomalies: Two Persistent Mysteries at the Intersection of Planetary Geoscience and Space Plasma Physics

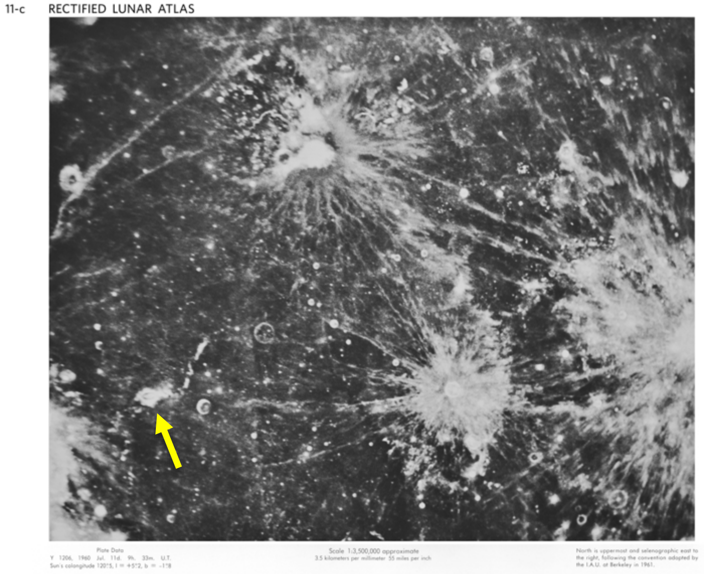

Lunar swirls in Mare Ingenii
*Kaguya* HDTV camera
crater near center is 9 km diameter

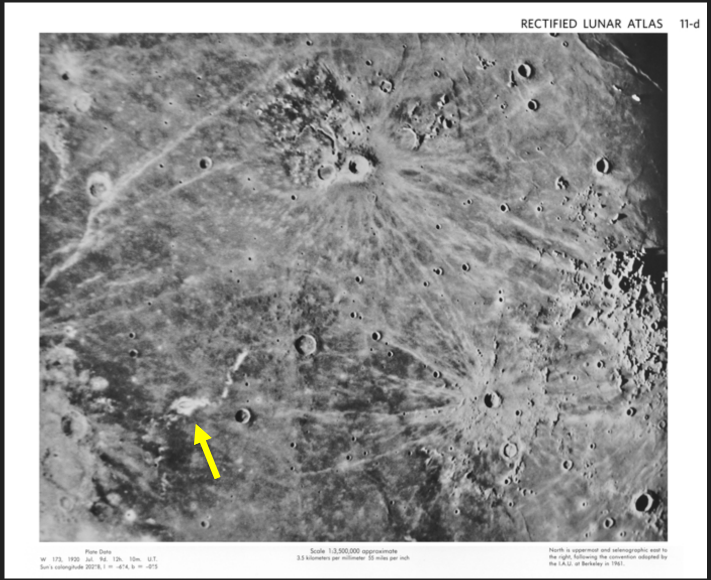



The range of space physics phenomena associated with the Moon's crustal magnetic anomalies
(Bamford et al., *ApJ* 2016)

# Lunar Swirls:
# A Persistent Mystery

- Reiner Gamma, the type example of a swirl, has been known since the early days of telescopic observations.




*Rectified Lunar Atlas*

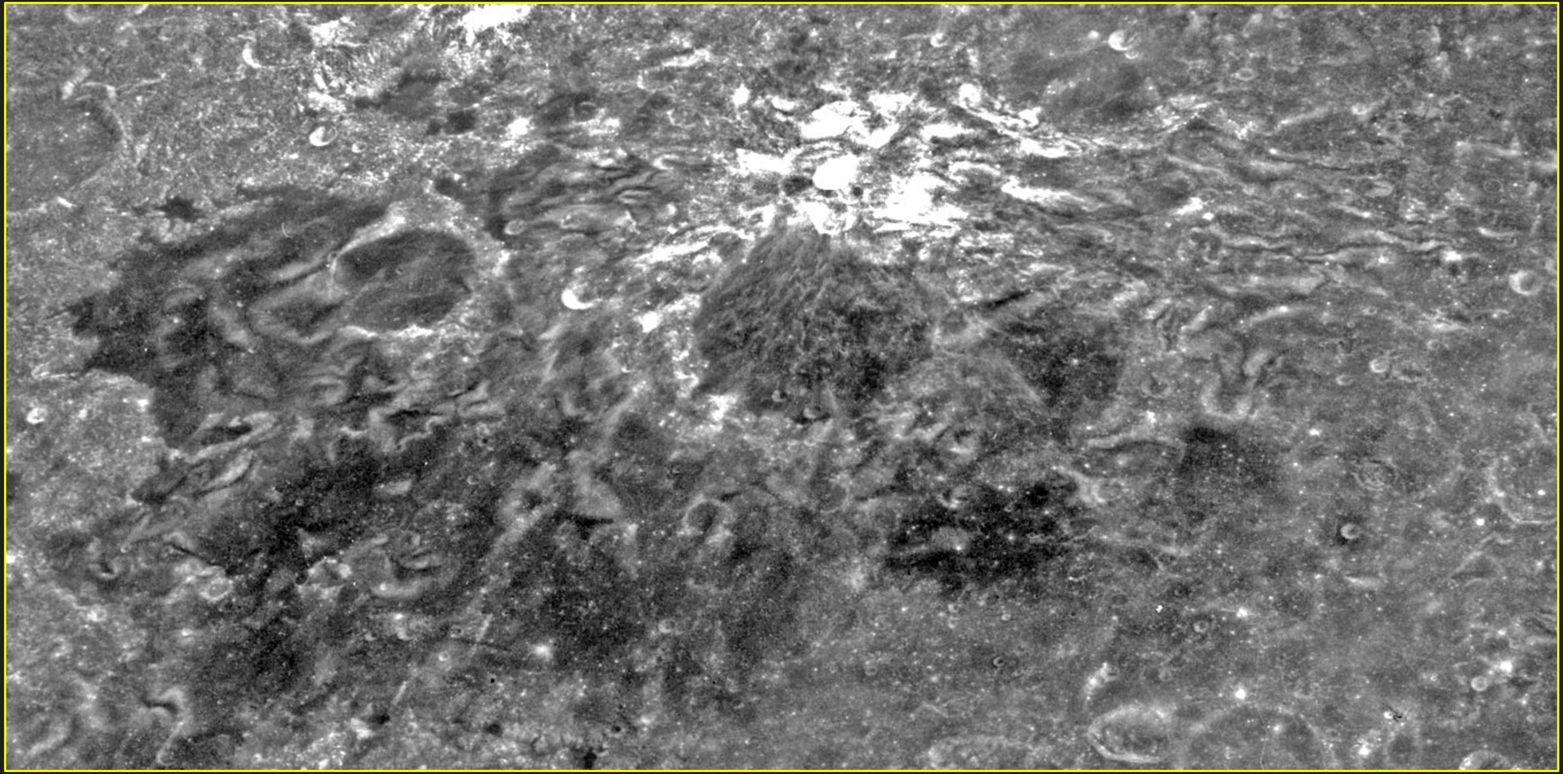
High Sun:
Yerkes, 1960

Low Sun:
Mt. Wilson, 1920

# Space Age: Swirls on the Farside

Mare Ingenii
*Lunar Orbiter II* (1966)
frame 075-M

# Space Age: Swirls on the Farside



Mare Marginis / Goddard A
*Apollo 8* (1968)
AS08-12-2208

# Space Age: Swirls on the Farside

- Swirls on the highlands.

Swirls near Firsov
*Apollo 10* (1969)
AS10-30-4365

# Lunar Swirls:
# A Persistent Mystery

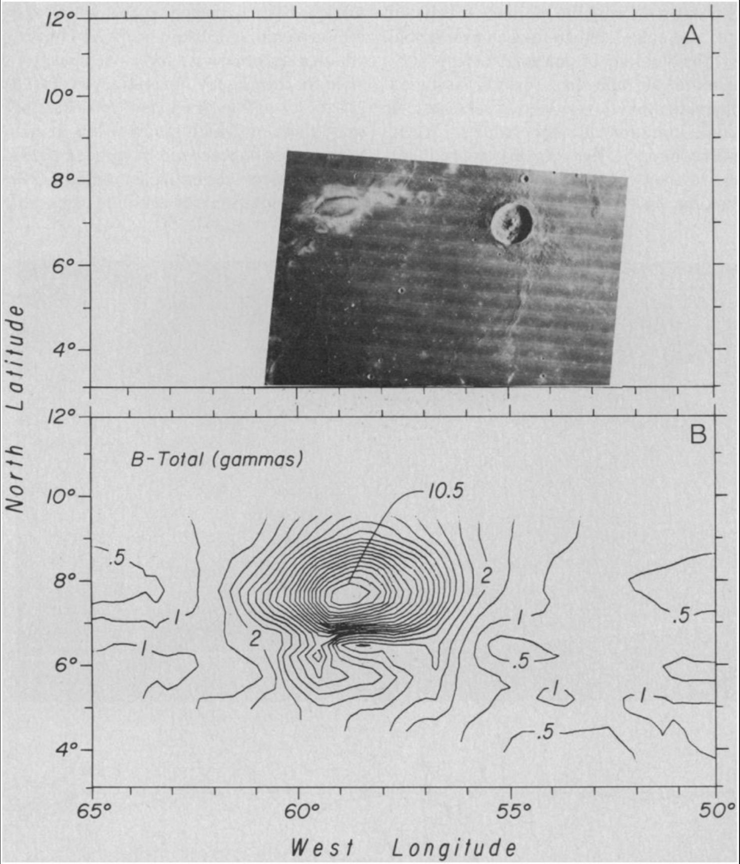
- Reiner Gamma detail – LROC.


LROC M1127569280

Looking east, north to the left.

# Lunar Swirls and Magnetic Anomalies: Two Persistent Mysteries

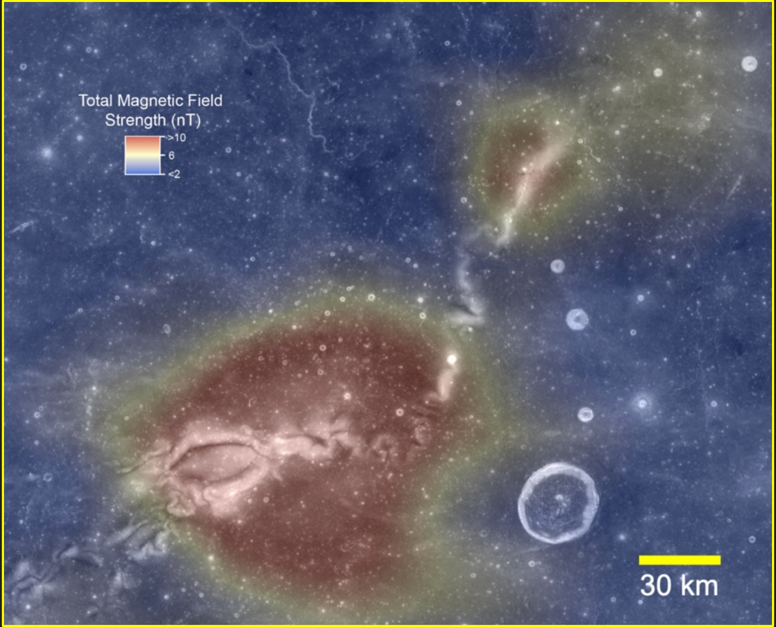
- *Apollo 15* and *Apollo 16* subsatellite magnetometer data revealed that Reiner Gamma is a magnetic anomaly.




Hood et al. (1979, *Science*)

# Lunar Swirls and Magnetic Anomalies: Two Persistent Mysteries

- More complete mapping of crustal fields from *Lunar Prospector* and *Kaguya*.
- Most magnetic anomalies are co-located with swirls.
- What is the origin of the magnetized crust?
- What is the origin of the swirls?
    - How are swirls related to the magnetic anomalies?




Reiner Gamma
LROC visible reflectance with color overlay of *Lunar Prospector* total magnetic field strength at 30-km altitude from Richmond and Hood (2008 *JGR*).

# Lunar Swirls: Hypotheses

## 1. Solar-Wind Standoff

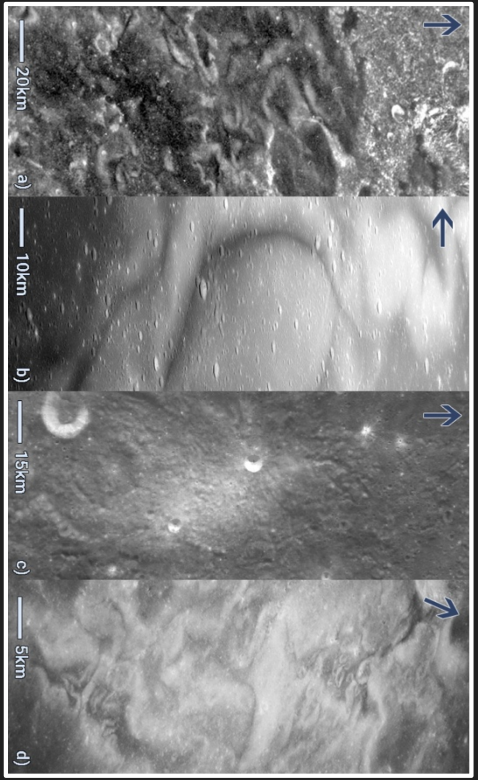
- Hood and Schubert (1980)
- Magnetic field attenuates the flux of solar-wind ions that reach the surface, slowing the normal space-weathering (soil-darkening) process caused by sputtering and implantation.

## 2. Comet-Related Impact

- Gas and dust in coma modifies the surface (Schultz and Srnka, 1980; Syal and Schultz, 2015).
- Nucleus fragments or meteoroid swarms scour/plow the the surface, exposing fresh material (Pinet et al., 2000; Starukhina and Shkuratov, 2004).

## 3. Unusual Dust Effects

- Electric fields induced by solar-wind/magnetic-field interactions cause electrostatically lofted dust to be attracted to or repelled from certain locations (Garrick-Bethell et al., 2011), possibly modifying the photometric properties (Pieters et al., 2014).
- Magnetic sorting of dust depending on submicroscopic metallic iron content (Pieters, 2018).




Mare Marginis *Apollo 8*

Reiner Gamma *LROC*

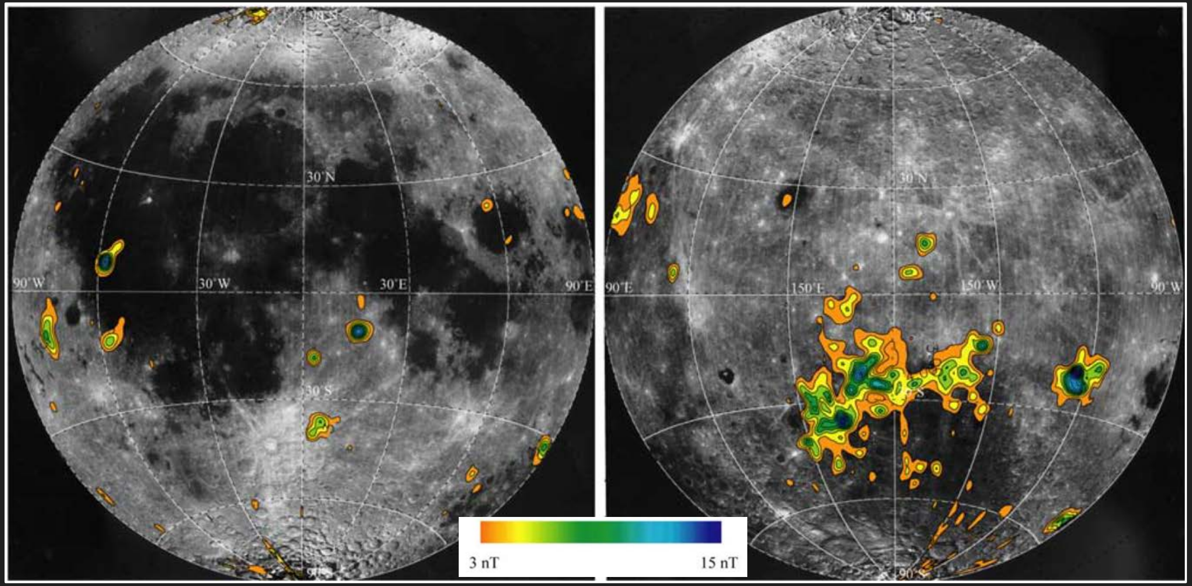
Descartes *LROC*

Firsov *Apollo 10*

Arrows point North.

# Magnetic Anomalies: Hypotheses

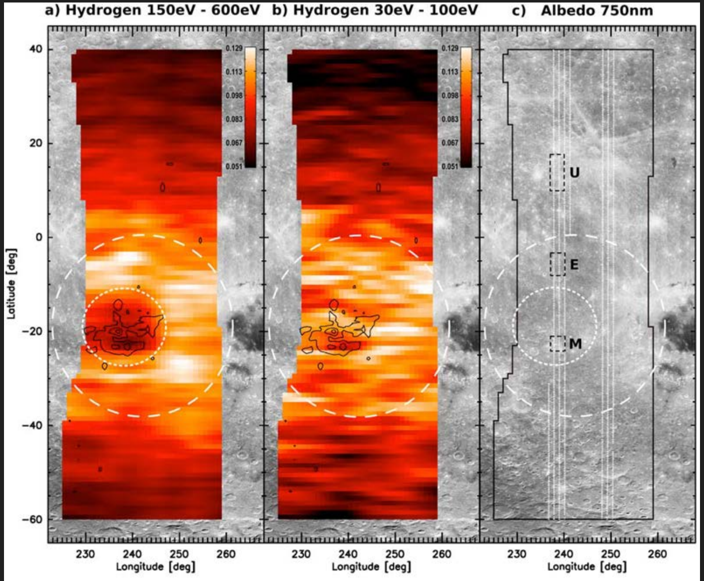
1. Basin ejecta magnetized in a transient or global dynamo field (Hood et al. 2001; Wieczorek et al., 2012).
2. Magnetization imparted by plasma interactions during a comet impact (Schultz and Srnka, 1980; Syal and Schultz, 2015).
3. Igneous material (buried dike or lava tube) that was magnetized in a global dynamo field (e.g., Garrick-Bethell, et al. 2009; Purucker, et al. 2012; Hemingway and Tikoo, 2018).



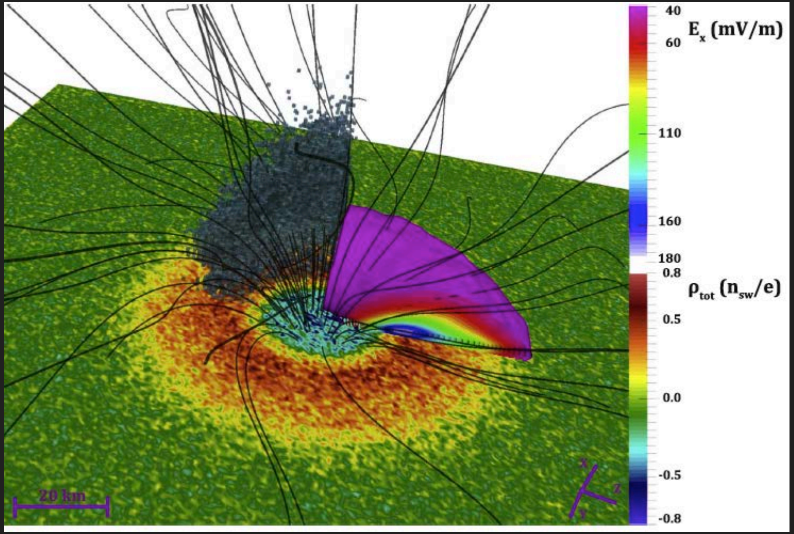

*Lunar Prospector* total magnetic field strength at 30-km altitude (Richmond and Hood, 2008 *JGR*).

# Plasma Phenomena

- The local crustal magnetic fields modify the interaction of the solar wind with the Moon.
- "Mini-magnetospheres" have been detected through observations of the magnetic field, neutral atoms, electrons, and solar-wind protons.
- Plasma interactions have also been studied via modeling.




*Kaguya* ENA measurement over the Gerasimovich magnetic anomaly/swirl (Wieser et al., 2010 *GRL*).




Modelled solar-wind interaction with a vertical dipole embedded in the lunar surface (Deca and Divin, 2016 *Astrophys. J.*)

# Selected Science Questions Associated with Lunar Magnetic Anomalies and Swirls

All traceable to NASA guiding documents – details in the white paper

a) *Planetary Magnetism*: What are the strength and structure of the magnetic field on the surface, and what are the implications for the origin of the magnetic anomalies?

b) *Space Plasma Physics*: How do magnetic anomalies interact with the incident plasma?

c) *Lunar Geology*: What are the nature and origin of lunar swirls?

d) *Space Weathering*: What are the roles and relative importance of ion/electron versus micrometeoroid bombardment in the optical alteration of silicate regoliths?

e) *Airless-Body Water Cycle*: How do hydration features vary with location/ magnetic-field strength/ion flux, lunar time of day, and among different regolith constituents (mineral/rock fragments, agglutinates, and impact or volcanic glasses)?

# Selected Science Questions Associated with Lunar Magnetic Anomalies and Swirls

All traceable to NASA guiding documents – details in the white paper

a) *Planetary Magnetism*: What are the strength and structure of the magnetic field [redacted] the implications for the origin of the magnetic anomalies?

b) *Space Plasma Physics*: How do magnetic anomalies interact [redacted]

c) *Lunar Geology*: What are the nature and origin [redacted]

d) *Space Weathering*: What are the [redacted] of ion/electron versus micrometeoroid bombardment in the [redacted] regoliths?

e) *Airless-*[redacted] hydration features vary with location/ magnetic-field strength/ion flux, [redacted] different regolith constituents (mineral/rock fragments, agglutinates, and [redacted] glasses)?

Answers to these questions can only be obtained by measurements on the surface within a magnetic anomaly.

# Measurement Requirements

1. Particles and Fields
    a. Strength and direction of magnetic field at different locations within a magnetic anomaly.
    b. Flux of plasma (ions, electrons) and energetic particles (including energetic neutral atoms, ENA) reaching the surface as a function of energy, angle, time of day, solar-wind/magnetosphere conditions, and local magnetic field strength/direction.
    c. Electric field strength.

2. Regolith and Dust
    a. Regolith texture, particle size distribution, and mechanical properties as a function of location, magnetic field strength, and plasma flux.
    b. Soil composition, maturity, and hydration as a function of location, magnetic field strength, and plasma flux.
    c. Observation of dust activity, including any correlations with the magnetic/plasma environment.

# Measurement Requirements

3. Site Geology and Lunar Geophysics
   a. Landing site context.
   b. Subsurface density variations.

# Mission Types

1. Stationary Lander
   - Single-point measurements, e.g., magnetic field, plasma, electric field, dust activity. Night survival would allow for time series.
   - Landing rocket exhaust disturbance precludes certain measurements related to regolith physical properties or hydration.

# Mission Types

2. Stationary Lander with Small Rover
   - 5–10-kg class rover: Drive tens of meters to ~1 km to make measurements away from rocket disturbance
   - Assess small-scale variations in the magnetic or plasma environment
   - Rover probably cannot survive the night
   - Rover too small to carry a full complement of instruments

3. Long-Range Rover
   - To fully address the science questions, measurements are needed across spatial scales comparable to the size of the magnetic anomalies as mapped from orbit and the size of the swirl albedo patterns. For example, the distance from near the center of the main Reiner Gamma bright area to the northern dark lane is ~7-10 km. The *Intrepid* mission study (Robinson et al. PMCS report) had a crisscrossing traverse of 259 km at Reiner Gamma over six months.
   - Rover in this size class could carry all the instruments necessary for a full investigation.

# Conclusions

- Lunar magnetic anomalies and lunar swirls are natural laboratories at the intersection of space physics with planetary geoscience.

- These locations are unique in that they present a venue for investigation of a broad group of topics in planetary science.

- The magnetic anomalies offer special conditions for testing hypotheses and providing answers to fundamental questions related to these topics, all within a relatively small area on the Moon's surface, convenient for design of landed missions.