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

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NASA's *Forward to the Moon Strategic Plan for Lunar Exploration* includes "Non-Polar Landers and Rovers" that will, by 2024, land "at a lunar swirl and [make the] first surface magnetic measurement." A surface mission to one of these unique locations would provide key data for answering important cross-cutting questions in planetary science – close-by on our nearest planetary neighbor. Progress toward answering these questions depends on interdisciplinary investigation carried out on the lunar surface. Here we outline the science case for a landed mission to a lunar magnetic anomaly, including illustration of the linkages to the documents that guide NASA's science planning. We also discuss the measurements and instruments that could address the science questions, and describe options for robotic lander and rover missions.

1. Introduction

The Moon presently lacks a global, internally generated magnetic field, but the lunar crust contains areas of magnetized rocks called "magnetic anomalies" [e.g., 1]. These crustal magnetic anomalies are frequently correlated with lunar swirls, unusual markings with high reflectance at visible wavelengths [2–6]. The origins of the magnetic anomalies are unclear. Magnetic anomalies have been suggested to be related to basin ejecta magnetized in a transient or global dynamo field [7, 8], magnetization imparted by plasma interactions during a comet impact [3, 9], and igneous material that was magnetized in a global dynamo field [e.g., 10–12]. Several of the magnetic anomalies are found diametrically opposite (antipodal) to large lunar impact basins such as Imbrium and Orientale [7]. However, the most famous of these features, at Reiner Gamma, is not antipodal to a major basin.

Regardless of their origin, the local magnetic fields modify the interaction of the solar wind with the Moon [e.g., 13, 14]. Described as "mini-magnetospheres", the plasma disturbances above the surface have been studied via modeling [e.g., 15–19] and detected through observations of the magnetic field [13], neutral atoms [20], electrons [21], and solar-wind protons [22].

The swirls have morphologies ranging from diffuse bright spots to complicated sinuous patterns [4]. Unlike other structures such as rilles or craters, lunar swirls have no detectable topographic expression and have surface roughnesses indistinguishable from the surrounding regolith [23, 24]. That is, they appear to represent markings imprinted on the surface. Several hypotheses for the origin of the swirls have been proposed. These include: a) a magnetic anomaly selectively shields the surface from the solar wind [1] and thus inhibits the normal space weathering process which darkens and reddens unshielded soil; b) the action of cometary gas and dust [3, 9, 25] or a meteoroid swarm [26] recently disturbed the surface, producing the bright swirl markings by scouring and changing the structure and particle-size distribution of the uppermost regolith; c) electromagnetic fields in these regions altered the trajectories of levitated, charged dust, leading to accumulation of high-reflectance dust in the swirls [27], or the dust motions disturbed the uppermost regolith producing high reflectance [28].

Swirls are perhaps the most beautiful class of features on the Moon. The nature and origin of the magnetic anomalies and swirls are longstanding mysteries in lunar science. The solutions to these mysteries will increase our knowledge of processes affecting all airless rocky bodies in the solar system [29].

2. Science Questions Associated with Lunar Magnetic Anomalies and Swirls

A lunar magnetic anomaly is a unique natural laboratory for addressing a wide range of questions in planetary science. These can be grouped into five broad topics.

a. *Planetary Magnetism*: What are the strength and structure of the magnetic field on the surface? What are the size and depth of the magnetic source(s)? A surficial anomaly would support a comet impact origin. A deep source might indicate a magnetized intrusion or a deposit of magnetized basin ejecta. What are the implications for an early dynamo and lunar thermal evolution?

b. *Space Plasma Physics*: How do magnetic anomalies interact with the incident plasma? What are the fluxes of the particles that actually reach the surface by energy and species? How important are electric fields? How does the solar wind/magnetic field/surface interaction vary over the lunar day and with changing ambient plasma conditions? Lunar mini-magnetospheres are part of the diversity of magnetospheric phenomena found in the solar system.

c. *Lunar Geology*: What are the nature and origin of lunar swirls? Are swirls ancient or recent? Has levitated dust or interaction with cometary material modified the Moon's surface? Are unsampled rock types with high metallic iron content [8, 12] implied by the strength of the magnetization, potentially pointing to unusual petrologic processes?

d. *Space Weathering*: What are the roles and relative importance of ion/electron versus micrometeoroid bombardment in the optical alteration of silicate regoliths? The magnetic anomalies offer control on one of the key variables in space weathering, solar-wind exposure, which is attenuated by the presence of the magnetic field, while micrometeoroids are not affected. Space weathering operates on airless surfaces across the Solar System [30] and complicates interpretation of spectral signatures. It is therefore important to thoroughly understand space weathering on the Moon, the cornerstone body for planetary science.

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)? Are both water and hydroxyl present on the sunlit surface? The high-reflectance areas of swirls exhibit weaker hydroxyl absorptions at $\sim 2.8 \mu\text{m}$ than does the surrounding regolith [31]. Is this observation related to a lower flux of solar-wind protons reaching the surface, or a difference in retention?

3. Science Traceability to NASA Guiding Documents

The topics and questions in Section 2 can be linked to the 2013 Planetary Decadal Survey and other NASA and lunar science community guiding documents. A landed-science workshop report [32] listed some of the linkages; we discuss them here in more detail.

3.1 Decadal Survey 2013-2022

The 2013-2022 Planetary Decadal Survey [33] lists a set of "Inner Planets Important Questions" (IPIQ). Here we describe how the IPIQ relate to the science of lunar magnetic anomalies and swirls.

A. *What are the major surface features and modification processes on each of the inner planets?* Subjects including space weathering, the formation of swirls, and comet impacts are all connected with planetary surface features and processes.

B. *How are planetary magnetic fields initiated and maintained?* The origin of lunar crustal magnetic fields relates to the history of the lunar dynamo, and potentially to impact processes (comets, large basins) that may have produced magnetized deposits.

C. *What are the compositions, distributions, and sources of planetary polar deposits?*

D. *How are volatile elements and compounds distributed, transported, and sequestered in near-surface environments on the surfaces of the Moon and Mercury?*

E. *What are the mechanisms by which volatile species are lost from terrestrial planets, with/without substantial atmospheres, and with/without significant magnetic fields?*

These three inter-related questions can all be addressed via investigation at a lunar magnetic anomaly. Solar-wind protons are a potential source of volatiles trapped in polar permanent shadow. Investigation of plasma fluxes and surface hydration within a magnetic anomaly will help to understand the solar wind as a source of volatiles and how OH and H₂O are transported on the surface of airless bodies like the Moon and Mercury. The role of magnetic fields in modulating creation and loss of volatiles in an airless surface can be studied in the natural laboratory of a lunar magnetic anomaly.

3.2 Scientific Context for Exploration of the Moon

The National Research Council's report *Scientific Context for Exploration of the Moon* [34] compiled a set of eight specific areas of scientific research (Science Concepts) for future lunar exploration. Here we show how six of these Concepts intersect with the science opportunities at lunar magnetic anomalies and swirls.

Concept 2. *The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body.* Solving the mystery of the origin of magnetic anomalies will give insights into the core dynamo and the Moon's thermal evolution.

Concept 3. *Key planetary processes are manifested in the diversity of lunar crustal rocks.* Rock magnetism is an aspect of crustal diversity. The magnetization of crustal rocks may indicate that unusual/unsampled rock types with high metallic iron content are present in the magnetic source bodies.

Concept 5. *Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.* The source body at some magnetic anomalies could be a dike or lava tube. Identifying such dikes or lava tubes would give insight into magmatic processes on the Moon.

Concept 6. *The Moon is an accessible laboratory for studying the impact process on planetary scales.* It is hypothesized that comet impacts or magnetized basin ejecta are involved in the origin of magnetic anomalies and swirls.

Concept 7. *The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.* A lunar magnetic anomaly is the best location to study the relative roles of solar-wind exposure vs. micrometeoroid bombardment in space weathering.

Concept 8. *Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.* Lunar magnetic anomalies are predicted to have unusual levels of levitated dust activity because of electric fields associated with interaction of the solar wind with the magnetic field. Dust accumulation may be a factor in the origin of lunar swirls.

3.3 SSERVI Transformative Lunar Science

The 2018 white paper on *Transformative Lunar Science* (TLS) commissioned by the Solar System Exploration Research Virtual Institute [35] examined key fundamental science issues that NASA could address through new lunar exploration initiatives. Here we show how three of these TLS issues can be addressed through in situ studies of lunar magnetic anomalies and swirls.

TLS (d). *Understand and utilize the special water cycle of the Moon and other airless bodies.* Lunar magnetic anomalies offer unmatched opportunities to investigate the linkages between solar-wind proton flux and creation and migration of OH/H₂O in the lunar surface.

TLS (e). *Characterize the Moon's interior to reveal how this differentiated neighbor of Earth formed and evolved.* Investigating the nature and origin of lunar crustal magnetization will yield

insights into the Moon's core dynamo and perhaps the role of intrusive magmatism (e.g., magnetized dikes).

TLS (f). *Evaluate the extended record of space weather and fundamental processes of plasma interactions with surfaces.* Study of space weathering and the influence of plasma interactions on surface processes are central to the science opportunities at magnetic anomalies and swirls.

3.4 LEAG Next Steps on the Moon

In 2018 the Lunar Exploration Analysis Group (LEAG)'s Report of the Specific Action Team on *Next Steps on the Moon* [36] identified lunar missions that could "provide openings to make dramatic, paradigm shifting advances in planetary science". Among the mission goals identified by NEXT-SAT was "Characterizing the formation of magnetic anomalies". The report specifically called out "In situ measurements of surface magnetic fields; radiation environment of swirls to understand solar wind interactions with surface" and mentioned both static landers and the need for mobility (rovers).

3.5 HEO Strategic Knowledge Gaps

At the direction of the NASA Human Exploration and Operations Mission Directorate (HEOMD), LEAG has developed a list of strategic knowledge gaps (SKGs) [37] that need to be closed in order to reduce risk, increase effectiveness, and improve the design of robotic and human space exploration missions. The SKGs are organized by Themes. Several of the Themes intersect with science that could be accomplished at a lunar magnetic anomaly and swirl.

Theme I, Resource Potential: I-D, temporal variability and movement dynamics of surface-correlated OH and H₂O. Lunar magnetic anomalies are ideal venues for elucidating the formation of hydration by the solar wind.

Theme II, Lunar Environment: II-B, radiation at the lunar surface. Could crustal magnetic fields provide useful shielding of humans or landed assets from solar or cosmic radiation?

Theme III, Living and Working on the Lunar Surface: III-B-1, lunar geodetic control. III-C-2, lunar surface trafficability. III-E, near-surface plasma environment. A lander or rover could photograph landmarks, improving geodetic control of images obtained from orbit. Rovers could perform soil mechanics experiments, either with dedicated instrumentation (such as a penetrometer) or by collecting images of rover tracks. Characterizing the near-surface plasma environment is one of the major science goals for a landed mission to a lunar magnetic anomaly.

4. Science Traceability: Measurements and Instruments.

In order to fully address the science topics and questions in Section 2, in situ measurements on the surface are necessary [38, 39] – they cannot be done from orbit. In this section we review the general categories of measurements/observations that are needed, along with instruments that could potentially carry them out.

4.1 Particles and Fields

a. *Strength and direction of magnetic field at different locations within a magnetic anomaly.* To constrain the origins of lunar magnetic fields, it is essential to determine the magnetic field strength and structure on the surface within a magnetic anomaly. High-quality vector magnetic field measurements on the lunar surface are crucial for determining the structure and constraining the origin of magnetic anomalies. If feasible, measurements of the magnetic field during descent to the landing site would provide additional constraints on the depth and strength of the magnetic source body [40, 41]

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.* These measurements would address the detailed physics of the solar wind-anomaly interaction, and the efficiency of shielding of the surface. ENA measurements will help to better understand how the precipitating solar wind ions interact/react with the surface. Measurements of this kind could be made by a Faraday cup or with an electrostatic analyzer, and with an energetic particle or ENA detector.

c. *Electric field strength.* Electric fields may be set up by plasma effects caused by the presence of the crustal magnetic fields, and electric fields related to charging of the spacecraft could influence the behavior of dust and solar-wind electrons. Thus, missions may consider including an electric field probe.

4.2 Regolith and Dust

a. *Regolith texture, particle size distribution, and mechanical properties as a function of location, magnetic field strength, and plasma flux.* The physical nature of the regolith [42] in and around magnetic anomalies is central to testing hypotheses for the origin of lunar swirls. There are a number of approaches that could be used separately or together to gather information on regolith physical properties, including: a microscopic imager for particle size-frequency distribution; photometric studies of images from a mast camera; thermal inertia and roughness on millimeter-centimeter scales from thermal-IR measurements; images of rover wheel tracks and wheel trenches for soil mechanics analysis; and a penetrometer.

b. *Soil composition, maturity, and hydration as a function of location, magnetic field strength, and plasma flux.* Measurements of regolith elemental/mineralogical composition, exposure degree, and hydration are key to improved understanding of space weathering in general, and the origin of swirls in particular. Instruments that contribute data of this type include: a vis-NIR spectrometer (extended to the 3- μm region for OH/H₂O, or to $\sim 6\ \mu\text{m}$ for H₂O) – in the form of a microscopic multispectral imager, or a mast-mounted spot spectrometer or multi/hyperspectral imager; Mössbauer spectrometer for nanophase iron content; XRF-XRD or APXS for additional mineralogical and elemental abundances; neutron spectrometer for abundance of hydrogen and other elements.

c. *Observation of dust activity, including any correlations with the magnetic/plasma environment.* The importance of electrostatic charging and lofting of dust on the lunar surface has long been an open question [43]. Magnetic anomalies have been proposed to be areas with unusual dust activity [27, 28]. Note that the emphasis here is on slow-moving surface dust, not detection of interplanetary dust particles or micrometeoroids. A camera system could search for horizon glow and look for changes in dust coatings on rocks or the spacecraft (especially after terminator passage). Dedicated dust instruments could gauge dust particle flux, charge, velocity, and mass.

4.3 Site Geology and Lunar Geophysics

a. *Landing site context.* At any site, it is important to understand the landscape in which other measurements are made. Thus, key payload elements include a descent imager providing nested-resolution images of the site during landing, a mast-mounted panoramic camera, and a means for construction of site digital terrain models (e.g., a stereo imager or lidar system).

b. *Subsurface density variations.* Several hypotheses for the origin of magnetic anomalies involve intrusions or deposits of material that potentially have density contrasts with the host rock. Means to detect such density variations include gravimetry and ground-penetrating radar.

5. Mission Categories: Accomplishing the Science Objectives

Instruments intended to make the measurements discussed in Section 4 could reach the lunar surface via a variety of mission scenarios. These range from a single instrument on a stationary, short-lived lander, to a long-range mobile laboratory with a payload tailored for a comprehensive investigation of a magnetic anomaly.

Currently available technologies and NASA's plans for lunar exploration suggest that three major robotic mission categories can be considered for investigation of magnetic anomalies:

5.1 Stationary Lander.

Early commercial landers in the Commercial Lunar Payload Services (CLPS) program, carrying instruments from the Payloads and Research Investigations on the Surface of the Moon (PRISM) program, are stationary landers designed to operate only during one period of lunar daylight. Single-day landers could collect key point data for the limited period of operation, whereas a lander that survives through multiple lunar days could provide an extended time series, e.g., plasma flux reaching the surface during different external conditions. However, a lander's rocket exhaust disturbs the surface [44], and hence could preclude certain types of measurements, especially those related to regolith physical properties or hydration.

5.2 Stationary Lander with Small Rover.

Several commercial entities plan to offer small rovers that could deploy from a lander. Such rovers could carry several kilograms of payload, and make traverses of tens to hundreds of meters from the lander, generally during a single lunar day. The ability to make measurements even at such relatively short distances away from the lander would be valuable. Examples including travel to nearby areas of lesser landing rocket disturbance, or assessment of small-scale variations in the magnetic or plasma environment. A lander+small rover mission could fit in the PRISM program.

5.3 Long-Range Rover.

To fully address the science questions identified in Section 2, 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 Reiner Gamma swirl has bright-to-dark transitions that range in length up to ~5 km [12]. The distance from near the center of the main Reiner Gamma central bright area to the northern dark lane is ~7-10 km [45]. A rover driving 7 km in a period of 10 Earth days would travel at an average speed of less than 1 cm/s, similar to the average speed of NASA Mars rovers. Thus, a rover could perform a linear traverse from the center to the edge of the Reiner Gamma magnetic anomaly in one lunar daylight period, creating measurement profiles with all of the instruments in the payload. A rover capable of night survival could conduct a series of traverses in order to perform areal mapping, thereby constraining the two-dimensional variations in regolith properties, magnetic and plasma conditions, etc.

For each mission category, the relative contribution of a particular instrument toward meeting the science goals may differ. For example, a magnetometer on a static lander with a lifetime limited to one lunar daylight period could measure the magnetic field strength and direction on the surface within a magnetic anomaly. This would be a valuable data point, because at present only values continued from spacecraft orbital altitudes are available. However, a magnetometer on a long-range, long-lived rover could assess magnetic field variations along traverses of ten or more kilometers in length. Such a capability would represent a much greater contribution to constraining the size, depth, strength, and coherence of the magnetized body, and hence offer strong tests of hypotheses for the origin of the magnetic anomaly.

A recent mission study [46] designed a lunar rover with a traverse of 1800 km lasting four Earth years. The plan includes an investigation of the Reiner Gamma magnetic anomaly with more than 30 major stops and over 100 minor stops distributed over a crisscrossing path of 259 km during six lunations. This mission, named *Intrepid*, has an instrument payload of ~17 kg. Both nuclear- and solar-powered versions were analyzed, and the costs were found to fit within the New Frontiers mission cap. A rover focused only on investigating a magnetic anomaly would be less costly, likely compatible with the Discovery program or a CLPS/PRISM mission. Commercial providers are developing rovers in the size class that would be needed for a magnetic anomaly mission, with or without night survival. As the *Artemis* program returns humans to the Moon, astronaut-tended versions of certain instruments can also be envisioned.

6. Summary and Conclusions

Lunar magnetic anomalies and lunar swirls represent a strange and wonderful intersection of space plasma physics with planetary geoscience. These locations are unique in that they present a venue for investigation of a group of broad topics in planetary science that are traceable to the Decadal Survey and other community guiding documents: planetary magnetism, space plasma physics, lunar geology, space weathering, and the water cycle on airless bodies. 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. In addition, missions targeted to a lunar magnetic anomaly and swirl will gather new data to spur new hypotheses. Such missions should be a priority for the U.S. and other nations.

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