MAGNETIC ANOMALY AS NATURAL LABORATORY: THE *LUNAR COMPASS* MISSION CONCEPT.

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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] (Fig. 1). The crustal magnetic anomalies are frequently correlated with unusual, often sinuous, high-reflectance markings known as lunar swirls [2–5].

The origin of the magnetic anomalies is unclear. They have been suggested to be 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, 11, 12].

Regardless of their origin, the local magnetic fields modify the interaction of the solar wind with the lunar surface [e.g., 13, 14]. Described as "mini-magnetospheres", the disturbances have been studied via modeling [e.g., 15] and detected through observation of the flux of neutral atoms [16], electrons [17], and solar-wind protons [18].

Several hypotheses for the origin of the high-albedo swirls have been put forward. These include: a) a magnetic anomaly shields the surface from the solar wind [1] and thus inhibits the normal soil-darkening process (space weathering) to which unshielded areas are subjected; b) the action of cometary gas and dust [3, 9, 19] or a meteoroid swarm [20] disturbs the surface, producing the bright swirl markings by changing the structure and particle-size distribution of the uppermost regolith; c) electromagnetic fields in these regions alter the trajectories of levitated, charged dust, leading to accumulation of high-reflectance dust in the swirls [21], or a disturbance of the uppermost regolith that produces high reflectance [22].

Key Planetary Science Questions: A lunar magnetic anomaly is a natural laboratory for addressing a range of questions in planetary science. These include:

a) *Planetary magnetism*: What are the strength and structure of the 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, buried beneath mare basalt. What are the implications for an early dynamo and lunar thermal evolution?

b) *Space plasma physics*: How does the magnetic anomaly interact with the incident plasma? How important are electric fields? What are the fluxes of the particles that actually reach the surface by energy and species? How does the solar wind/magnetic field/surface interaction vary over the lunar day and with ambient plasma conditions?

c) *Lunar geology*: What are the nature and origin of the lunar swirls? Are they ancient or recent? Has levitated dust or cometary material modified the surface? Are unsampled rock types with high metallic iron content [12] implied by the strength of the magnetization?

d) *Space weathering*: What are the roles and relative importance of ion vs. micrometeoroid bombardment in the optical alteration of silicate regoliths? The magnetic anomalies offer some control on one of the key variables, solar wind exposure, because micrometeoroids are not affected by the presence of the magnetic field. Space weathering operates on airless surfaces across the Solar System 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) *Lunar water cycle*: The high-reflectance areas of swirls exhibit weaker hydroxyl absorptions at 2.82 μm than the background, consistent with a lower flux of solar-wind protons reaching the surface [23] or a difference in retention. How does this hydration feature vary with location/magnetic field strength and between different regolith constituents?

Exploration SKGs: Measurements within a magnetic anomaly would also address Strategic Knowledge Gaps (SKGs) for human exploration. SKG Themes include: Theme I, Resource Potential: I-D, temporal variability and movement dynamics of surface-correlated OH and H_2O. Theme II, Lunar Environment: II-B, radiation at the lunar surface. 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 Rover Mission: A suitably instrumented traverse of a magnetic anomaly is needed to definitively answer the above important questions [24]. We have named our rover mission concept *Lunar Compass*.

Two instruments characterize the magnetic and plasma environment on the lunar surface. Vector magnetometer measurements will define the surface field and constrain the depth, geometry and strength of the magnetic source region [25]. A solar-wind spectrometer will directly measure the charged-particle flux reaching the surface.

A second set of instruments focuses on characterizing the regolith: a mast-mounted stereo color imager to assess surface morphology; a UV-VNIR-SWIR spectrometer to obtain mineralogy, measure hydration, and characterize space weathering; and a microscopic spectral imager for particle size distribution, regolith texture, and spectral properties.

Other potential instruments include an XRF or APXS for elemental abundances; a Mössbauer spectrometer to measure nanosize iron content, an electric field probe, a gravimeter, and a dust accumulator.

An estimate of the traverse distance necessary to achieve the science goals can be made by considering the Reiner Gamma magnetic anomaly and swirl (Fig. 2). Initial operation would be a linear traverse from the center of the high-reflectance part of the swirl north to cross the dark lane, a distance of ~7 km. Extended mission operations could use additional transects to more extensively map the magnetic field, solar-wind flux, and regolith properties.

Conclusions: The *Lunar Compass* mission provides an opportunity to establish the nature and origin of lunar magnetic anomalies, lunar swirls, the processes of surface space weathering, inputs to the lunar water cycle, and the Moon's charged particle environment, as well as helping to close exploration SKGs. Moreover, the mission is achievable within the constraints of a Discovery-class mission.

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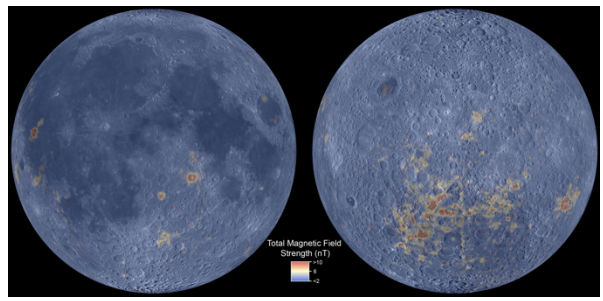

Fig. 1. Global map of lunar magnetic anomalies derived from *Lunar Prospector* magnetometer data [26], overlain on LROC WAC 689-nm basemap.

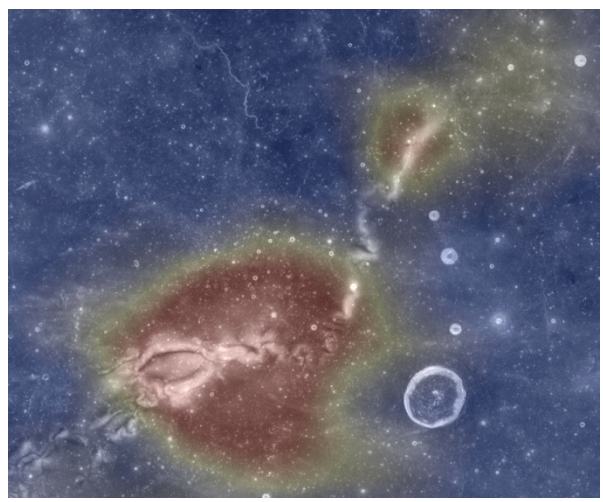

Fig. 2. Excerpt of the map in Fig. 1, showing the Reiner Gamma swirl (7.4° N, 301.0° E). Reiner crater (lower right) is 27 km in diameter. The peak field strength over Reiner Gamma is ~22 nT.