EXPLORATION OF A LUNAR CRUSTAL MAGNETIC ANOMALY: THE *LUNAR COMPASS* ROVER MISSION CONCEPT.

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Introduction: The Moon does not currently possess a global, internally generated magnetic field, but the lunar crust does contain areas of magnetized rocks ("magnetic anomalies" [e.g., 1], Fig. 1). The crustal magnetic anomalies are often correlated with unusual, sinuous, high-reflectance markings called lunar swirls [2, 3, 4, 5] (although the swirls are less reflective than the surroundings in the far ultraviolet [6]).

The source of magnetization has been suggested to be magnetized basin ejecta [7]. Another hypothesis contends that the magnetic anomalies were created by plasma interactions during impact of a cometary coma with the lunar surface [3, 8].

Regardless of the origin, the local magnetic fields produce disturbances in the interaction of the solar wind with the lunar surface [e.g., 9, 10]. Described as "mini-magnetospheres", the disturbances have been detected through analysis of the flux of neutral atoms [11], electrons [12], and solar-wind protons [13].

Several hypotheses for the origin of the high-albedo swirls have been put forward. One states that the magnetic anomaly "stands off" (shields the surface from) the solar wind [1], and thus inhibits the normal soil darkening process (space weathering) to which unshielded areas are subjected. Other workers suggest that impact of a cometary nucleus/coma [3, 8, 14] or meteoroid swarm [15] could disturb the surface to produce the bright swirl markings by changing the structure and particle-size distribution of the uppermost regolith. Alternatively, the electromagnetics of these regions could alter the trajectories of levitated, charged dust. These grain motions might lead to accumulation of high-reflectance dust in the swirls [16], or could disturb the uppermost regolith structure and thus produce high reflectance [17].

The lunar magnetic anomalies present a natural laboratory for at least four major areas in planetary science:

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

b) Space plasma physics: How does the magnetic anomaly interact with the incident plasma to form a standoff region? 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 change with time of lunar day?

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?

d) Space weathering: What are the roles and relative importance of ion and micrometeoroid bombardment? The lunar magnetic anomalies offer some control on one of the key variables, solar wind exposure, because micrometeoroids should not be affected by the presence of the magnetic field. Space weathering operates on airless surfaces across the Solar System, and it is important to develop a complete understanding of space weathering on the Moon, the cornerstone body for planetary science.

e) Lunar water cycle: It is known from orbital data that the high-reflectance parts 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 [18] or a difference in retention. How does this hydration feature vary on the lunar surface, and with location/magnetic field strength?

A Rover Mission: An instrument package traversing one of the major magnetic anomalies could help to provide answers to the important questions listed above [19]. We have named our rover mission concept *Lunar Compass*.

Two elements of the package characterize the magnetic and plasma environment on the lunar surface. Vector magnetometer measurements will define the surface field and help to constrain the depth and thickness of the magnetic source region [20]. A solar wind spectrometer will directly measure the solar-wind flux reaching the surface, testing the solar-wind shielding model for swirls.

A second group of instruments focuses on characterization of the regolith: an X-ray fluorescence spectrometer to determine elemental abundance; a UV-VNIR-SWIR spectrometer to obtain mineralogy, measure hydration, and characterize space weathering; a Mössbauer spectrometer to measure nanophase iron content; a mast-mounted multispectral imager to assess surface morphology and composition; and a microscopic spectral imager for particle size distribution, regolith texture, and spectral-compositional properties.

An estimate of the traverse distance necessary to achieve the baseline science goals can be made from Fig. 2, which shows radial distance contours centered on the Reiner Gamma swirl. The initial operation would likely 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. Depending on the findings, extended mission operations could involve the rover moving in a grid pattern to more extensively map the magnetic field, solar-wind flux, and regolith properties.

For reference, *Lunokhod 2* traversed 37 km on the surface and, to date the Mars rover *Opportunity* has covered a distance of ~43 km; *Curiosity* has driven ~15 km. The operations of the *Lunokhod 2* mission (which also carried a magnetometer) provide guidance for how the *Lunar Compass* mission would be conducted. The short Earth-Moon communications delay and the more benign lunar terrain would offer a lunar rover less need for autonomy than robots driving on Mars. High spatial resolution maps (images, digital terrain models, and slope maps) are available from data obtained by the *Lunar Reconnaissance Orbiter* Camera (LROC) Narrow Angle Camera, hence routes could be well planned in advance and the rover "joy-sticked" in real time by a human operator on Earth.

Conclusions: The *Lunar Compass* mission provides an opportunity to define the nature of lunar magnetic anomalies, lunar swirls, the processes of surface space weathering, and the Moon's charged particle environment. The mission is potentially achievable within the constraints of a Discovery-class mission.

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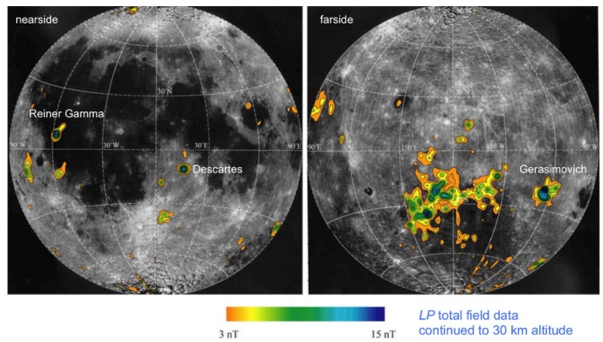

Fig. 1. Map of lunar magnetic anomalies derived from *Lunar Prospector* magnetometer data [21]. The strongest anomaly (28 nT at 30 km altitude) is that near crater Gerasimovich (Crisium basin antipode region). The strongest nearside anomaly is at Descartes (24 nT), in the highlands south of the *Apollo 16* landing site. Reiner Gamma's strength is 22 nT [12].

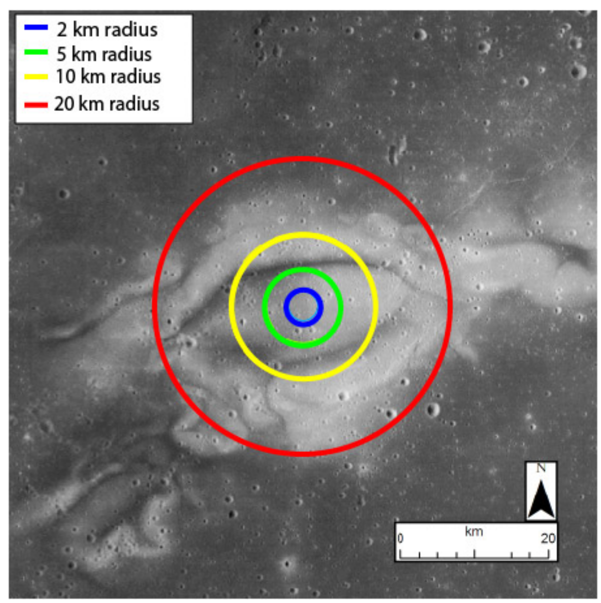

Fig. 2. LROC WAC global mosaic base map (100 m/pixel) with distance contours from the center of the Reiner Gamma swirl.