THE *LUNAR COMPASS* ROVER MISSION CONCEPT: EXPLORING A MAGNETIC ANOMALY. Brett W. Denevi[1], David T. Blewett[1], Dana M. Hurley[1], Joshua T.S. Cahill[1], Rachel L. Klima[1], Lauren M. Jozwiak, Jeffrey B. Plescia[1], Christopher P. Paranicas[1], Benjamin T. Greenhagen[1], Charles A. Hibbitts[1], Brian J. Anderson[1], Haje Korth[1], George C. Ho[1], Jorge I. Núñez[1], Michael I. Zimmerman[1], Pontus C. Brandt[1], Sabine Stanley[1], Joseph H. Westlake[1], Antonio Diaz-Calderon[1], and Jeffrey R. Johnson[1]. [1]Space Science Branch, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, Md., USA. (brett.denevi@jhuapl.edu).

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 often correlated with unusual, sinuous, high-reflectance markings known as lunar swirls [2–5] (although the swirls are less reflective than the surroundings in the far ultraviolet [6]).

The origin of the magnetic anomalies is unclear. They have been suggested to be magnetized basin ejecta [7], comet impact plasma interactions [3, 8], and remnants from a global field.

Regardless of the origin, the local magnetic fields modify 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. 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) impact of a cometary nucleus/coma [3, 8, 14] or meteoroid swarm [15] 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 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].

Key Planetary Science Questions: The lunar magnetic anomalies present a natural laboratory for addressing key questions in planetary science. These include:

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(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 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 over the lunar day?

c) *Lunar geology*: What is 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 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 it is important to develop a complete understanding of 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 [18] or a difference in retention. How does this hydration feature vary on the lunar surface and with location/magnetic field strength?

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: An instrument payload traversing a magnetic anomaly could help to provide answers to the important questions listed above [19]. We have named our rover mission concept *Lunar Compass*.

Two instruments 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 ion flux reaching the surface, testing the solar-wind shielding model for swirls.

A second set of instruments focuses on characterization of the regolith: a mast-mounted multispectral imager to assess surface morphology and composition; 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, and a traverse gravimeter. A laser retroreflector would be useful for general lunar geodetic studies.

An estimate of the traverse distance necessary to achieve the baseline science goals can be made by considering the Reiner Gamma magnetic anomaly and swirl (Fig. 2). 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 spiral or 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 offer advantages compared with 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 operated in real time from Earth.

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

References: [1] L.L. Hood and G. Schubert (1980), *Science 208*, 49–51. [2] F. El-Baz (1972), *Apollo 16 PSR*, NASA SP-315, 29-93–29-97. [3] P.H. Schultz and L.J. Srnka (1980), *Nature 284*, 22–26. [4] D.T. Blewett et al. (2011), *J. Geophys. Res. 116*, E02002. [5] B.W. Denevi et al. (2016), *Icarus 273*, 53–67. [6] J.T.S. Cahill et al. (2016) LPSC 47, #2991. [7] L.L. Hood et al. (2001), *J. Geophys. Res. 106*, 27825–27840. [8] M. Bruck Syal and P. Schultz (2015), *Icarus 257*, 194–206. [9] C.T. Russell and B.R. Lichtenstein (1975), *J. Geophys. Res. 80*, 4700–4711. [10] C. Lue et al. (2011), *Geophys. Res. Lett. 38*, L03202. [11] M. Wieser et al. (2010), *Geophys. Res. Lett. 37*, L05103. [12] J.S. Halekas et al. (2008), *Planet. Space Sci. 56*, 941–946. [13] Y. Saito et al. (2010), *Space Sci. Rev. 154*, 265–303. [14] P.C. Pinet et al. (2000), *J. Geophys. Res. 105*, 9457–9476. [15] L. Starukhina and Y. Shkuratov (2004), *Icarus 167*, 136–147. [16] I. Garrick-Bethell et al. (2011), *Icarus 212*, 480–492. [17] C.M. Pieters et al. (2014), *LPSC 45*, #1408. [18] G.Y. Kramer et al. (2011), *J. Geophys. Res. 116*, E00G18. [19] D.T. Blewett et al. (2010), *Ground-Based Geophysics on the Moon*, #3009. [20] L.L. Hood and J.S. Halekas (2010), *Ground-Based Geophysics on the Moon*, #3021. [21] N. Richmond and L. Hood (2008), *J. Geophys. Res. 113*, E02010.

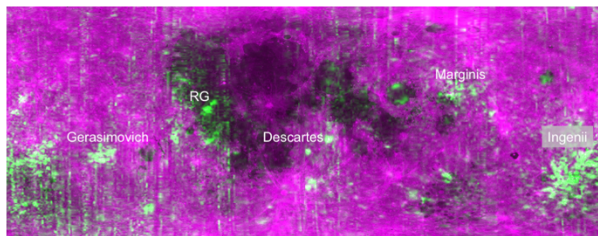

Fig. 1. Map of lunar magnetic anomalies derived from *Lunar Prospector* magnetometer data [21], overlain on LROC WAC 689-nm basemap. The strongest anomaly (28 nT at 30 km altitude) is that near crater Gerasimovich (Crisium basin antipode region). The strongest nearside anomaly is at Descartes (24 nT), in the highlands south of the *Apollo 16* landing site. Reiner Gamma's strength is 22 nT.

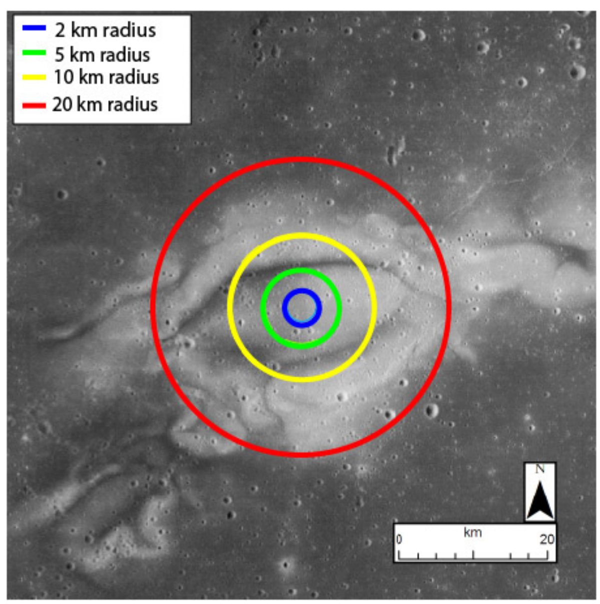

Fig. 2. LROC WAC global mosaic base map (100 m/pixel) with distance contours from the center of the Reiner Gamma swirl.