The Lunar Swirls

A White Paper to the NASA Decadal Survey

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Abstract

The lunar swirls are high albedo curvilinear surface features that are not associated with a particular lithology or typical lunar surface process. Each swirl is coincident with a local region of strong remanent magnetism on a body that does not currently generate its own magnetic field. There are at least three different models for swirl formation. Determining the true nature and formation mechanism of the swirls, their occurrence on the lunar surface, and why they are associated with magnetic anomalies will affect our understanding of the history of the Earth-Moon system, the interaction of planetary surfaces with the solar wind, and how we explore planetary surfaces.

List of Abbreviations	
Ga	Billions of years ago
H^+	Ionized hydrogen
IR	Infrared light
NIR	Near-infrared light
$npFe^0$	Nanophase iron
XRF/XRD	X-ray fluorescence/X-ray diffraction
VIS	Visible light
UV	Ultraviolet light

1 Science Objectives

Key questions in planetary science that can be addressed by surface measurements in a lunar magnetic/albedo anomaly include:

1. Lunar geoscience: the origin of lunar swirls
2. Planetary magnetism: the source of the magnetizing filed responsible for the crustal anomalies (a) early core dynamo, or (b) amplification of ambient fields by plasmas generated by basin-forming impacts
3. Space weathering: a process affecting interpretation of remote-sensing observations of all airless rocky Solar System bodies. Confirmation of solar-wind sputtering/implantation as a major contributor to the optical effects of space weathering would be a significant new step.
4. Fundamental plasma physics: the interaction of the solar wind with small-scale magnetic anomalies.

1.1 Significance

The National Research Council decadal survey in planetary exploration (NRC, 2003) listed several long-term objectives and goals. A mission to place instrumentation within a lunar magnetic anomaly is strongly relevant to Question 11 ("How do the processes that shape the contemporary character of planetary bodies operate and interact?"), through an integrated study of surface/solar wind/magnetic field interaction, regolith evolution, and impact cratering. Additionally, such a mission addresses Question 1 ("What processes marked the initial stages of planet and satellite formation?") by investigating the nature and origin of lunar crustal magnetic anomalies, and hence providing information on an early core dynamo.

2 Physical Characteristics of Swirls

The term *lunar swirls* describes a large number of unusual, sinuously shaped, high albedo features found across the Moon's surface [1, 2, 3]. Swirls have been identified on the lunar maria and highlands, and are coincident with regions of strong crustal magnetic fields. Their characteristic high spectral reflectance signal cannot be directly related to a spectrally distinct lithology [4, 5, 6, 7]. At the resolution of current data, the swirls appear to overprint the topography on which they lie, indicating that they are quite thin or a surface manifestation of an underlying phenomenon that is manipulating normal surface processes. Swirls on the maria are characterized by strong albedo contrasts and complex, sinuous morphology, whereas those on highland terrain may be less prominent and exhibit simpler shapes such as single loops or diffuse bright spots. Their curvilinear shape is often accentuated by low albedo regions that wind between the bright swirls. Attempting to delineate the bright swirls from the dark lanes in detail one will soon impinge upon the spatial limits of current imaging instrument data. This indicates a finer-scale structure and complexity that may resolve some of the remaining questions in different swirl origin models.

2.1 Association with Magnetic Anomalies

One generally accepted fact is that lunar swirl are closely associated with magnetic anomalies although not every magnetic anomaly (especially weaker ones) has a visually identifiable swirl. The Moon has no currently active dynamo with which to generate a magnetic field, and it is debated whether one ever existed [8, 9, 10, 11]. Nevertheless, orbital mapping by the Apollo 15 and 16 subsatellites and Lunar Prospector show regions of remanent magnetism antipodal to several large impact basins formed between 3.8-3.9 Ga [12]. Magnetization of these antipodal regions could occur in the presence of an amplified magnetic field. An amplified field could result from a plasma cloud generated by the basin forming impact interacting with a weak magnetic field present at the Moon at the time of basin formation [13, 14, 15]. The magnetized surface could be also due to impact-induced currents and seismic waves ringing the planet [16]. An unusually thick and/or strongly magnetized deposit of basin ejecta can be invoked to explain swirls, such as the Reiner Gamma Formation (Fig. 1), that are not antipodal to a basin.

3 Three prevailing models for lunar swirl formation

The **solar wind deflection** model proposes that the swirls represent exposed silicate materials whose albedos have been selectively preserved over time via deflection of solar wind ion bombardment by pre-existing strong crustal magnetic fields [2]. According to this model, optical maturation of exposed silicate surfaces in the inner solar system is at least partly a function of the solar wind ion bombardment. This model suggests that swirl formation is a continuing process, which dates from the era of basin formation.

The **cometary impact** model argues that the high albedo of the swirls depict scouring of the top-most surface regolith and exposure of fresh material by relatively recent cometary impacts [3, 6]. According to this model, the associated strong magnetic anomalies are the result of magnetization of near-surface materials heated above the Curie temperature through hyper-velocity gas collisions and micro-impacts. Proponents of the cometary impact model consider the occurrence of many swirls antipodal to relatively young, major basins to be coincidental or the result of incomplete mapping of swirl locations.

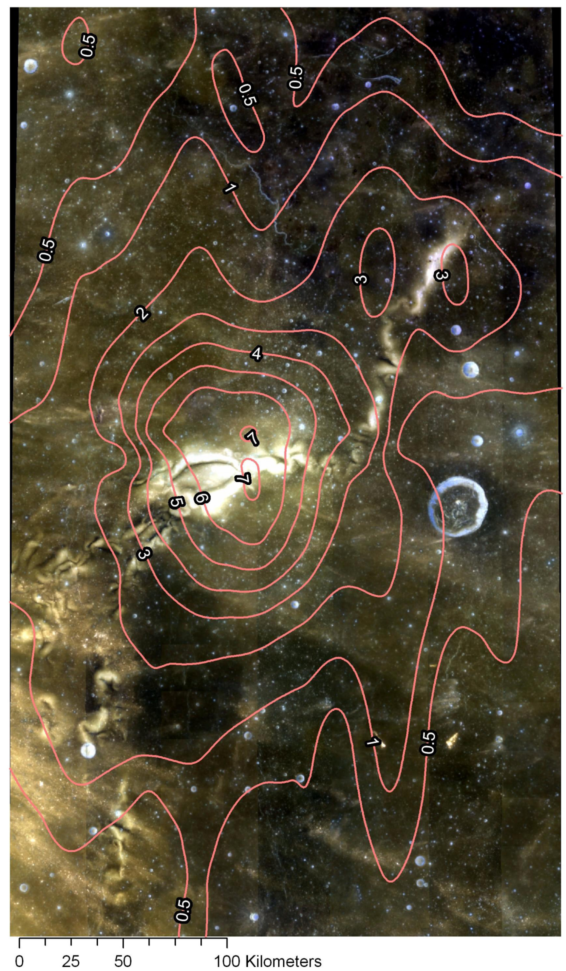

Figure 1: Clementine "natural color" mosaic, sinusoidal projection with north to the top. Lunar Prospector total magnetic field strength at 35.5 km altitude. Contour lines are labeled in nT.

The **meteoroid swarm** model is a variation of the cometary impact model. Here the cometary nuclei are fragmented by tidal forces attributed to the Earth and/or Sun before they encounter the lunar surface [17]. During and immediately after impact, inter-particle collisions in the cloud of debris and regolith particles of the ejecta collide with each other, forming the curvilinear swirl features. The final dust fragments of a swarm may form a halo with albedo and color differences from the substrate around the main part of the swirl. The meteoroid swarm hypothesis does not account for magnetic anomalies associated with lunar swirls nor the occurrence of several swirls antipodal to major basins.

3.1 Lunar Swirls as a Tool to Study Space Weathering

Space weathering is a process that affects the surfaces of all airless Solar System bodies. In the case of the Moon, space weathering causes initially bright crater rays to fade with time, and causes the reflectance spectrum of a mature soil sample to differ greatly from that of freshly powdered lunar rock. The effects of space weathering include an overall decrease in visible to near-IR reflectance, reduction in the contrast of diagnostic mineralogical absorption bands and introduction of a strong ”red” spectral slope [18]. These changes are attributed to the production of tiny blebs and coatings of metallic iron, known as nanophase iron [npFe^0, 19, 20]. The process responsible for production of the npFe^0 is not well understood, but is believed to be related to reduction of ferrous iron (Fe^{2+}) in minerals and glasses and deposition of vapors during micrometeoriod impact and solar wind sputtering [e.g. 21, 22, 23]. There is controversy concerning the extent to which implanted solar wind protons (H^+) aid in the reduction of Fe^{2+} to npFe0. Some workers [e.g. 24] contend that vapor deposition is sufficient and that the presence of solar wind H^+ as a reducing agent is not necessary. The lack of evidence for water as a byproduct of the reduction of FeO to npFe^0 in returned lunar samples also argues against solar wind implantation as a necessary contributor to space weathering.

According to the solar wind deflection model for the origin of swirls the magnetic anomaly stands off the solar wind, preventing it from reaching the surface and thus preserving a high albedo [2, 25, 26]. Thus it may be that the presence of a magnetic anomaly maintains the high albedo of unweathered material exposed by impacts. In addition, immature ray material originating at distant impacts that is deposited within the magnetically shielded area could contribute to the high reflectance of the swirl. The preservation of high reflectance occurs even though a magnetically shielded surface would still suffer micrometeoroid bombardment, which is also considered to be an agent of space weathering [e.g. 19]. Focusing of the solar wind flux by the magnetic anomaly could cause “overmaturation” and thus explain the dark lanes. The relative importance of solar-wind sputtering versus micrometeoroid impact has been a matter of debate. If lunar crustal magnetic anomalies, which can generate mini-magnetospheres [27, 28, 29], are responsible for protecting soils from the process(es) that produce the optical effects associated with maturation, then by implication the solar wind is the dominant agent of space weathering, because a magnetic anomaly would not screen out micrometeoroids [30]. Such a process is supported by new results from the Japanese lunar mission, Kaguya, which has shown conclusively that solar wind ions are slowed and deflected, and largely reflected, above the strongest crustal magnetic anomalies [31].

3.2 Other reasons to study the lunar swirls/magnetic anomalies:

Solar wind ions (hydrogen, helium, and other trace elements) implanted in the upper regolith are the primary source of lunar volatiles at most latitudes. The focusing effect of crustal magnetic fields may produce concentrations of these volatiles in areas peripheral to or between strong crustal fields (i.e., in the ”overmatured” dark lanes). Regolith with enhanced solar-wind content could be useful from a resource extraction perspective. Similarly, it may be advantageous to locate an outpost in an area that experiences a low degree of solar wind bombardment. For example, levitation of electrically charged fine dust on the lunar surface has received considerable attention [e.g., 32, 33]. It could be that areas protected from ion implantation are less susceptible to charging of the dust.

4 Mission/Instruments Recommendations

The origin of the lunar swirls is a major outstanding puzzle in lunar geoscience. Significant progress toward resolving this puzzle could be made by a rover mission to measure the surface magnetic field and solar wind flux at various points within the bright and dark portions of a swirl. The ability to spatially resolve this level of detail is not possible with an orbiter. The rover should also be equipped with a spectrometer capable of characterizing the regolith elemental abundance (with XRF/XRD), mineralogy (via UV-VIS-NIR spectroscopy), and in terms of npFe^0 content (via Mössbauer spectroscopy). Although not integral, solar wind plasma studies would be enriched by

List of Abbreviations

Instrument	Objective
High-resolution color imager	Surface morphology and composition
Microscopic imager	Particle size distribution
VIS-NIR spectrometer	Surface mineralogy
Vector magnetometer	Surface magnetic measurements
Solar wind particle detector	Measure solar wind flux at the surface
Mössbauer spectrometer	Mineralogy, abundance of $npFe^0$
XRF/XRD	Elemental and mineralogical composition

an orbiter carrying plasma instrumentation at the same time, so that the orbiter can measure the undisturbed solar wind plasma flux with the population that makes it down to the surface in the vicinity of the anomalies.

If it is found that no solar wind flux reaches the surface in areas of high magnetic field strength, and this corresponds to areas of high albedo and low $npFe^0$ content, then the solar wind deflection model is favored. A mission to characterize the solar wind and magnetic environment within a magnetic and albedo anomaly such as the Reiner Gamma formation thus provides a unique opportunity to test the solar wind deflection model for the origin of lunar swirls and to determine the role of the solar wind in space weathering of the regolith.

5 Final Word

Our objectives are directed at understanding the nature of lunar magnetic anomalies, the mechanism of space weathering, and assessing the major geological processes of impact cratering and regolith maturation. We believe that these objectives require the in situ experiments and implementation described below. Remote observations from orbit cannot provide the necessary types of data.The objectives of the rover mission include:

1. Determining the elemental, mineralogical, and spectral characteristics of the regolith and assessing the extent to which the soil has been affected by space weathering;

2. Determining the solar wind and magnetic field environment at the lunar surface;

3. Providing ground truth for calibration of compositional orbital remote sensing;

Regardless which hypothesis for swirl origin is supported by the results of such a mission, our findings will lead to a greatly improved understanding of the causes of space weathering. Space weathering is a process that occurs throughout the Solar System, and the information gained from the natural laboratory provided by the Reiner Gamma Formation and other magnetic anomalies on the Moon is necessary for an accurate interpretation of remote sensing observations of any airless body such as Mercury, asteroids, dwarf planets, and moons. Indeed, it has recently been suggested that anomalous color on asteroids could be indicative of the presence of a magnetic field [34]. In addition, better models for space weathering on the Moon will lead to a more quantitative understanding of the lunar optical maturity parameter [35, 36] and may open the door to remote age dating of crater rays. Study of the magnetic anomaly will also help to determine its source, and the data will be important for testing hypotheses of the origin of the lunar magnetic field. Time variations in the field intensity at various solar wind conditions will be used to evaluate the suggestion that a mini-magnetosphere exists at sites of crustal magnetic anomalies [27].

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