MAGNETIC AND SPECTRAL PROPERTIES OF LUNAR SWIRLS, AND A NEW MECHANISM FOR THEIR FORMATION. I. Garrick-Bethell[1], J. W. Head III[1], and C. M. Pieters[1], [1]Department of Geological Sciences, Brown University, 1846 Brook Street, Providence, RI 02912, Ian_Garrick-Bethell@brown.edu.

Introduction: Bright swirl-shaped features on the Moon have remained one of the most enigmatic lunar geologic features [1, 2]. Generally, lunar swirls have high albedo, low optical maturity, and often exhibit dark lanes that interweave with brighter features. Swirls are also correlated with magnetic anomalies [3]. Traditionally, there have been two classes of hypotheses to explain swirls. The first suggests that impacts of comets or meteoroids scoured away the mature surface layers of lunar soil, leaving behind bright, immature material [4-6]. The second hypothesis suggests that the magnetic fields associated with swirls stand off the solar wind protons, and prevent the maturation of the underlying soil [3, 7]. The first hypothesis has difficulty explaining the strong crustal magnetization observed at swirls, while the second cannot account for the lack of obvious micrometeoroid weathering at swirls.

Here we present two new sets of observations about lunar swirls, both of which motivate a new hypothesis for their formation. The new formation mechanism makes use of the electric fields that are inferred to exist at lunar crustal magnetic anomalies, and electrostatic dust lofting processes.

Magnetic field strengths at swirls: Under the solar wind stand off model, dark lanes form in swirls due to the deflection and focusing of protons in areas that are otherwise shielded [3]. The width of these darker regions should be limited by the gyrodiameter of protons as they spiral to the surface. Several dark lanes at Reiner Gamma have widths of ~600 m, Figure 1. Assuming a proton pitch angle of 45° and a velocity of 400 km/s, the near-surface magnetic field required to produce a gyrodiameter of 600 m is 12,000 nT. This estimate is a minimum, since the motion of the protons will not be perfectly adiabatic.

Such high fields near the surface require significantly magnetized material. For example, modeling the magnetic anomaly as a magnetized disk of radius 2 km (typical swirl length scale), height 2 km (typical mare thickness), and buried just below the surface, the required magnetization is ~20 A/m. However, the most magnetic lunar samples ever measured have magnetizations of ~1 A/m. Therefore, either the materials at Reiner Gamma are unusually magnetic, which itself is an interesting conclusion, or the solar wind stand off hypothesis is incomplete. Considering the expected micrometeoroid weathering at swirls, and observations of the spectral properties of swirls (below), we will explore the latter scenario.

Spectral characterization of lunar swirls: Differences in space weathering on a normal mare surface can be visualized by plotting band strength (950/750 nm) vs. albedo (750 nm) [8]. Pixels from a large surface area will form a linear trend in this plot, with mature soils plotting in the upper left corner, and immature soils plotting in the lower right. The solar wind standoff model predicts that soils within swirls should plot on the lower right corner of the background trend. However, soils within swirls form independent linear trends that are displaced from each other in band strength and albedo, when moving outward from the center of the swirl (Figure 2). If solar wind and micrometeoroid bombardment produce the same nanophase iron as the main weathering agent that creates the normal linear weathering trend, the observed multiple trends is inconsistent with the solar wind stand off model.

Swirl formation by transport of fine dust: We seek a model for swirl formation that permits micrometeoroid weathering, explains the association with magnetic fields, explains the spectral properties of swirls, and explains the structure of dark lanes. The model is based on the observations of weak electric fields at the crustal magnetic anomalies at the Apollo 12 and 14 sites [9-13]. These electric fields form by charge separation, due to the differential penetration of solar wind electrons and protons into the magnetic field. Positive voltages at each site were inferred from observations of particle accelerations by Apollo surface instrumentation. For the Apollo 12 site the 38 nT magnetic field produced a ~100 V potential, with a length scale of 5 km, producing an electric field of $\sim 2 \times 10^{-2}$ V/m, in agreement with the estimate in [14]. Similarly, at the Apollo 14 site (~75 nT) the electric field is inferred to be $\sim 5 \times 10^{-2}$ V/m.

In a process that is unrelated to crustal magnetic fields, fine lunar dust is lofted above the surface by electric fields. This phenomenon has been observed by a number of spacecraft and instruments [15-19], at altitudes above the lunar surface ranging from centimeters to kilometers. The exact mechanism of lofting is not known, but a number of observations suggest it operates mainly in the terminator region.

In our model we assume that fine dust is lofted twice a day at each terminator crossing. The average lofting time for a grain is unknown, but models suggest between seconds and minutes [16, 20]. The size of lofted grains is also not well known, but is likely below 10 μm in diameter [16]. We assume the grain is at an equilibrium potential of 10 V, and calculate its charge following [21].

In Figure 3 we show that lunar dust of up to 10 μm can be transported over the length scales of swirls in time periods that are comparable to the solar wind weathering timescale (100,000 yr [22]), for reasonable lofting times (>3 s) and electric fields (< 50 mV/m). Smaller dust grains are more easily transported. Because fine dust (< 45 µm) dominates the spectral properties of lunar soil and the < 10 um fraction is the most weathered [23], this transport process may lead to spectral properties similar to what is observed at swirls.

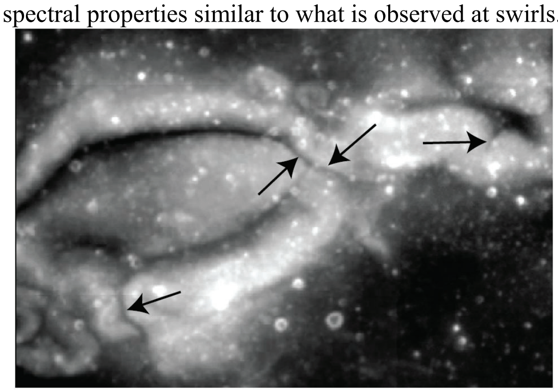

Figure 1: Reiner Gamma swirl. Arrows indicate dark lanes with widths less than ~600 m.

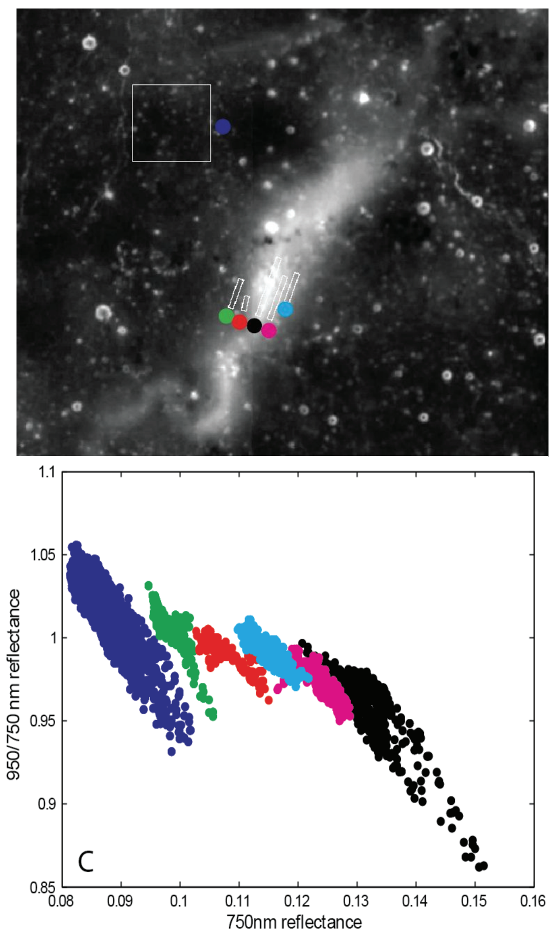

Figure 2: Swirl north of Reiner Gamma swirl. Top: Locations for pixels shown in bottom panel. Bottom: Band strength vs. albedo trends for rectangles in top image. Dark blue pixels represent the background weathering trend.

We note that crustal magnetic anomalies exert attractive or repulsive forces on the magnetic dipoles of fine dust. However, there is an equal probability of repulsion and attraction, making the net effect likely small, even if other difficult conditions are met.

Dark lane formation. Under the dust transport model, dark lanes can be explained by regions where the net horizontal electric field is zero, and dust transport is halted. Such regions may be due to adjacent positive electric anomalies that nullify each other's fields, or symmetric charge distributions that create internal regions of zero horizontal field.

Conclusions: Horizontal fine dust transport is a viable mechanism to explain the unusual weathering trends at lunar swirls. The model can be further tested with better topography and spectral data.

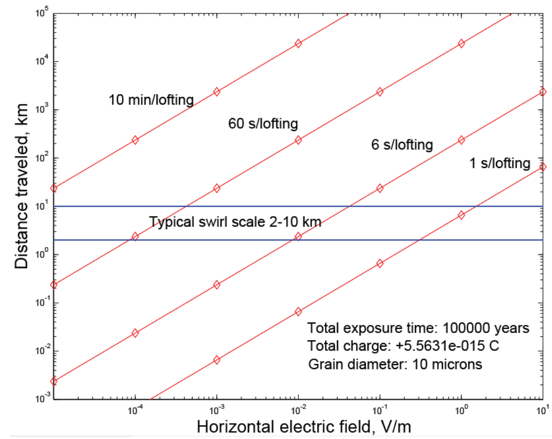

Figure 3: Transport distance for a 10 µm lunar dust grain at 10 V, for a variety of horizontal electric fields and lofting times. Assumes the grain is lofted twice each lunar day, and the probability of lofting is unity at each lofting opportunity.

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