SPECTRAL PROPERTIES OF LUNAR SWIRLS AND THEIR FORMATION BY DUST TRANSPORT.

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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 within 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 micrometeoroids scoured away the mature surface layers of lunar soil, leaving behind bright, immature material [1, 4]. The second hypothesis suggests that the magnetic fields associated with swirls stand off the solar wind, and prevent the maturation of the underlying soil [2, 3]. The first hypothesis has difficulty explaining the strong crustal magnetization observed at swirls, while the second cannot account for the apparent lack of micrometeoroid weathering at swirls, and the existence of swirls at locations with relatively modest magnetic fields (e.g. Mare Marginis).

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

Spectral characterization of lunar swirls: Differences in space weathering on a normal mare surface can be visualized by plotting a proxy for band strength (950/750 nm) vs. albedo (750 nm) [5]. 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. This trend is illustrated as Trend 2 in Figure 1 (bottom), for background soils at Mare Ingenii (Figure 1, top). The solar wind standoff model predicts that soils within swirls should experience less weathering and plot in the lower right corner of this trend. However, soils within swirls form independent linear trends that are displaced from each other in band strength and albedo (Trend 1 in Figure 1).

Feldspathic component of swirls. Trend 1 is similar to what is observed after a small highlands component of soil is added to a mare soil. For example Staid and Pieters [6] found that when mare locations were contaminated with highlands ejecta, their maturity trend was broadened and displaced in the same direction in 750 nm reflectance as described above. Bell and Hawke [7] found that Reiner Gamma swirl was best modeled as a mixture of immature mare material and a small component of highlands material. However, there is no other observational indication of mixing with highlands material at Reiner Gamma.

We suggest that this apparent highlands component is actually an enrichment in fine-grained feldspathic material. Unusually abundant fine grained material could create such an feldspathic enrichment because the finest fraction of both mare and highland soils are naturally feldspar rich [8, 9].

Swirl formation by transport of fine dust: We seek a model for swirl formation that permits micrometeoroid weathering, explains the association with magnetic fields, and explains the unique spectral properties. The model is based on the observations of weak electric fields at the crustal magnetic anomalies at the Apollo 12 and 14 sites [10-14]. 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 ~2 × 10^{-2} V/m, in agreement with the estimate in [15]. Similarly, at the Apollo 14 site (~75 nT) the electric field is inferred to be ~5 × 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 many spacecraft and instruments, e.g. [16-19], at altitudes above the lunar surface ranging from centimeters to kilometers. The exact mechanics of lofting are not known, but a number of observations suggest it operates mainly in the terminator region.

In our model we assume that charged 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 [17, 20]. The diameter of lofted grains is also not well known, but is likely <10 μm [17]. We assume the grain is at an equilibrium potential of 10 V [21], and calculate its charge following [22].

Note that even if dust lofting is only active in the terminator region, the solar wind can still interact with the crustal magnetic field to produce the required electric field. Furthermore, lunar dust movement has been observed ~60 hours (3° at the equator) after sunrise or before sunset [18], such that dust lofted at the terminator may arrive at a more fully solar-wind exposed magnetic anomaly.

In Figure 2 we show that charged 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 (10^5 years [23]), for reasonable lofting times (>3 s) and electric fields (< 5 × 10^{-2} V/m). Smaller dust grains are more easily transported.

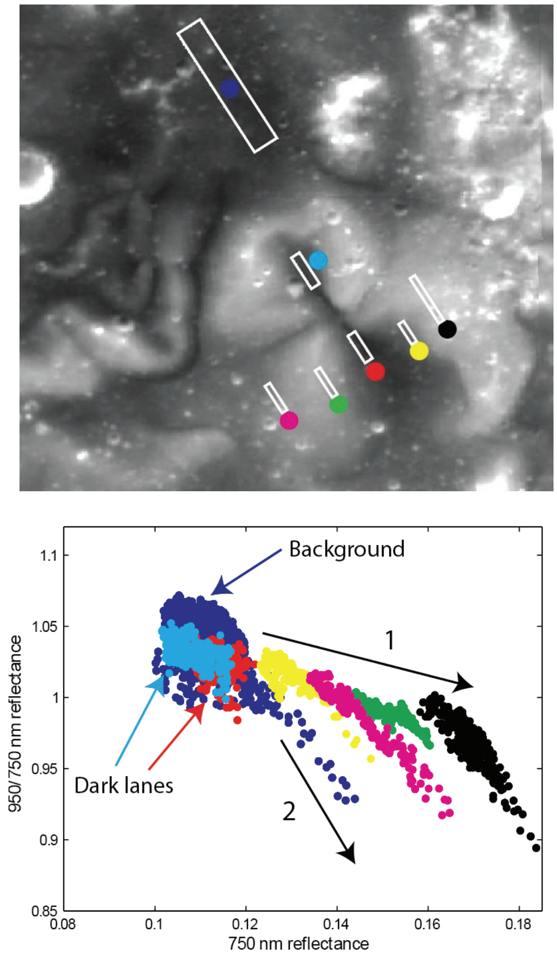

Figure 1: Swirl in Mare Ingenii. Top: Locations for pixels shown in bottom panel. Bottom: 950/750 nm reflectance vs. 750 nm reflectance for rectangles in top image. Trends 1 and 2 are discussed in the text.

Swirl color production. The fundamental spectral observations that constrain the swirl forming process are: 1) Swirls are higher in albedo, 2) Swirls appear slightly enriched in a component that mimics highlands or feldspar rich material, 3) Swirl material apparently has higher band strength than the surrounding material. The most cohesive hypothesis to explain the spectral data is that positively (negatively) charged fine dust is being repelled (attracted) into bright areas. Because fine dust is brighter and more feldspar rich [9], this would explain the first two spectral constraints. However, the finest dust is also expected to have weak band strength [9], in conflict with the third observation. Two possible resolutions are 1) the transport process is rapid enough to ensure that newly created dust is deposited fast enough to bury material before it weathers, altering the local steady state equilibrium [24], and 2) the dilution of local materials with finer, more transparent materials increases the optical path length to enhance local absorption bands.

Dark lanes. Under the dust transport model, dark lanes may be 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 horizontal fields, or symmetric charge distributions that create internal regions of zero horizontal field. While this mechanism is broadly consistent with observations, it is speculative, and cannot be strongly constrained with available data.

Conclusions: Horizontal dust transport is a viable mechanism to explain the unusual weathering trends at lunar swirls. Improved spectral measurements from the Moon Mineralogy Mapper, and inferences about grain size from thermal inertia calculations would be of particular utility in testing the model.

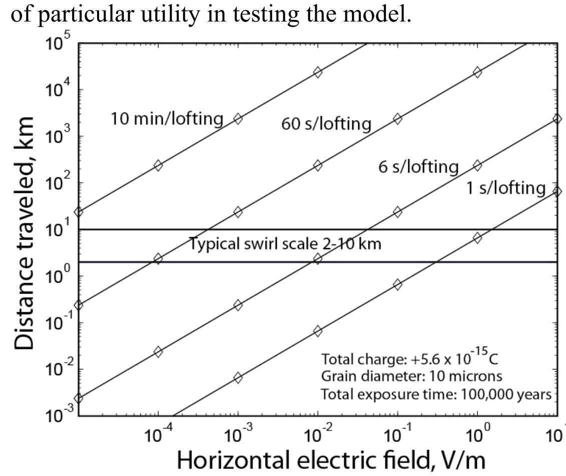

Figure 2: Cumulative transport distance for a 10-µm-diameter dust grain at 10 V, after 10^5 years, for a variety of electric fields and lofting times. Assumes the grain is lofted twice each day, and the probability of lofting is unity at each lofting opportunity.

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