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Spectral properties, magnetic fields, and dust transport at lunar swirls

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Lunar swirls are albedo anomalies associated with strong crustal magnetic fields. Swirls exhibit distinctive spectral properties at both highland and mare locations that are plausibly explained by fine-grained dust sorting. The sorting may result from two processes that are fairly well established on the Moon, but have not been previously considered together. The first process is the vertical electrostatic lofting of charged fine dust. The second process is the development of electrostatic potentials at magnetic anomalies as solar wind protons penetrate more deeply into the magnetic field than electrons. The electrostatic potential can attract or repel charged fine-grained dust that has been lofted. Since the finest fraction of the lunar soil is bright and contributes significantly to the spectral properties of the lunar regolith, the horizontal accumulation or removal of fine dust can change a surface's spectral properties. This mechanism can explain some of the spectral properties of swirls, accommodates their association with magnetic fields, and permits aspects of weathering by micrometeoroids and the solar wind.

1. Swirl models and observations

1.1. Previous swirl models

Bright swirl-shaped features on the Moon have remained one of the most enigmatic lunar geologic features (El-Baz, 1972; Hood and Schubert, 1980; Schultz, 1976; Schultz and Srnka, 1980). Generally, lunar swirls have high albedo, low optical maturity, and often exhibit dark lanes that interweave with brighter features (Fig. 1). Swirls have morphology that varies between diffuse patches and sinuous curves (Blewett et al., 2007). Swirls are also correlated with magnetic anomalies (Hood and Williams, 1989; Richmond et al., 2005), some of which are antipodal to major basins. If there is any topographic relief at swirls, it must be below tens of meters, since it is not detectable with existing photographic data sets.

No completely satisfactory model for swirl formation has emerged (Lucey et al., 2006). One class of hypotheses suggests recent (<100 Myr) impacts (Pinet et al., 2000; Schultz and Srnka, 1980; Starukhina and Shkuratov, 2004; Shkuratov et al., 2010) scoured away dark, mature material to reveal fresh unweathered soil, but these models do not easily explain the swirl association with magnetic anomalies (Richmond et al., 2005; Nicholas et al., 2007). Alternatively, Hood and Schubert (1980) proposed that local magnetic fields may form mini-magnetospheres that stand off the solar wind, thereby preventing maturation of the underlying soil.

Although the impact model has some deficiencies, a possible correlation between swirls and fresh craters has been noted, such as at Goddard A (Schultz and Srnka, 1980), and the albedo anomaly near Descartes (Blewett et al., 2005a,b) (Section 2.3). A possible explanation may be that the solar wind stand-off hypothesis is correct, and fresh material emplaced in magnetized regions weathers more slowly than surrounding non-magnetized regions, thereby forming a swirl. Nonetheless, after billions of years, newly emplaced material in magnetic regions may eventually reach a state of background maturity. Thus regions with fairly strong magnetic anomalies may have no swirls if they have not received any relatively fresh material. An alternative explanation to the possible correlation with fresh craters, however, is that fresh craters near swirls only appear to be relatively fresh because the swirl forming process affects spectral maturity parameters, and these craters are in fact older than they appear to be.

If correct, the solar wind stand-off model would elegantly explain both the brightness of swirls and their association with crustal magnetism, and it has therefore emerged as a leading candidate for swirl formation. However, there are a number of difficulties with the model that have not yet been fully addressed. For example, one objection is that micrometeoroids are unimpeded by magnetic fields (Richmond et al., 2003) and cause the same space weathering effects in timescales of ~100 Myr for the present micrometeoroid flux (Sasaki et al., 2001, 2003; Brunetto et al., 2006), still less than the 2–4 billion year old background surface ages of most swirls. While this is a valid concern, it is possible that the solar wind weathering time may be rapid (~1 Myr) (Hapke, 2001; Brunetto and Strazzulla, 2005; Strazzulla et al., 2005; Vernazza et al., 2009), and mere modifications in the rate of solar

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