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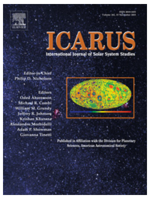

The distribution and extent of lunar swirls

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ABSTRACT

The mysterious high-reflectance loops and ribbons known as swirls are not uncommon on the Moon, but are apparently unique to this body. We mapped their distribution and extent using ultraviolet–visible images from the Lunar Reconnaissance Orbiter Camera. We find two main geographic groupings of swirls (South Pole–Aitken Basin and Marginis–King) and a host of smaller features including swirls near craters Abel, Crozier, Dewar, and Dufay X. All mapped swirls are associated with magnetic anomalies and swirls have magnetic field strengths shifted to higher values than their background, though there is not a 1:1 correspondence between the locations of swirls and magnetic anomalies. Swirls are also found in regions with iron abundances shifted to higher-than-background values, which could indicate that their formation is inhibited by low iron content. The most distinguishing characteristic of swirls is a low 321/415 nm ratio coupled with moderate to high reflectance, and swirls generally have high optical maturity (OMAT) parameter values, stronger 1-μm bands, and shallower normalized continuum slopes than their surroundings, consistent with a surface that has experienced less space weathering. However, some swirls cannot be discerned in OMAT or band-depth images. Areas with low 321/415 nm ratios but non-distinct visible–near-infrared properties could be related to the presence of fresh silicates or a glassy component that does not have a substantial abundance of embedded large submicroscopic iron grains (i.e., a difference in the agglutinate fraction of the soil). Swirl color properties vary with distance from Copernican and some Eratosthenian craters; their association with Eratostheninan craters suggests fresh material may be preserved longer in swirls than in non-swirl regions.

1. Introduction

Among the myriad of beautiful lunar landscapes, albedo markings known as “swirls” may be among the most intriguing and confounding. With boundaries that are sometimes diffuse, sometimes sharp, they meander across the surface with no apparent regard for topographic or geologic variations beneath, as if painted with a giant brush (Fig. 1). Reiner Gamma, the tadpole-shaped swirl extending over 100 km across Oceanus Procellarum (McCauley, 1967), may be the type example, and swirls at Mare Marginis, Firsov crater, Mare Ingenii, (Strom and Whitaker, 1969; Whitaker, 1969; El-Baz, 1972) and a host of others are known (see list in Blewett et al., 2011). These swirls range from large groupings of many complex loops and ribbons to a single isolated feature (Blewett et al., 2011); scales are typically in the tens of kilometers, and groupings of swirls can cover hundreds of kilometers.

Early work hypothesized that swirls could be volcanic deposits, such as from a felsic nuée ardente (McCauley, 1967), sublimates (Whitaker, 1969; El-Baz, 1972), or the products of chemical alteration from volcanic gases (El-Baz, 1972). However, two key sets of observations shaped subsequent formation theories. First, it was recognized that swirls are associated with crustal magnetic anomalies (Hood et al., 1979b; Hood and Schubert, 1980). Second, the spectral properties of swirls are similar to those of Copernican craters and ejecta, as first noted for Reiner Gamma (Hood et al., 1979b). This second point was repeatedly confirmed across the electromagnetic spectrum. From short to long wavelengths, the spectral properties of swirls are similar to those of fresh impact craters and ejecta and include: low far-UV reflectance values (Hendrix et al., 2015); steep UV slopes (Denevi et al., 2014); high visible–near-infrared reflectance and low 950/750 nm ratio values (Blewett et al., 2011; Kramer et al., 2011a); shallower visible–near-infrared continuum slopes and stronger mafic (1 and 2 μm) absorptions (e.g., Bell and Hawke, 1981; Kramer et al., 2011b); and thermal-infrared Christiansen Feature wavelengths shifted to short values (Glotch et al., 2015).

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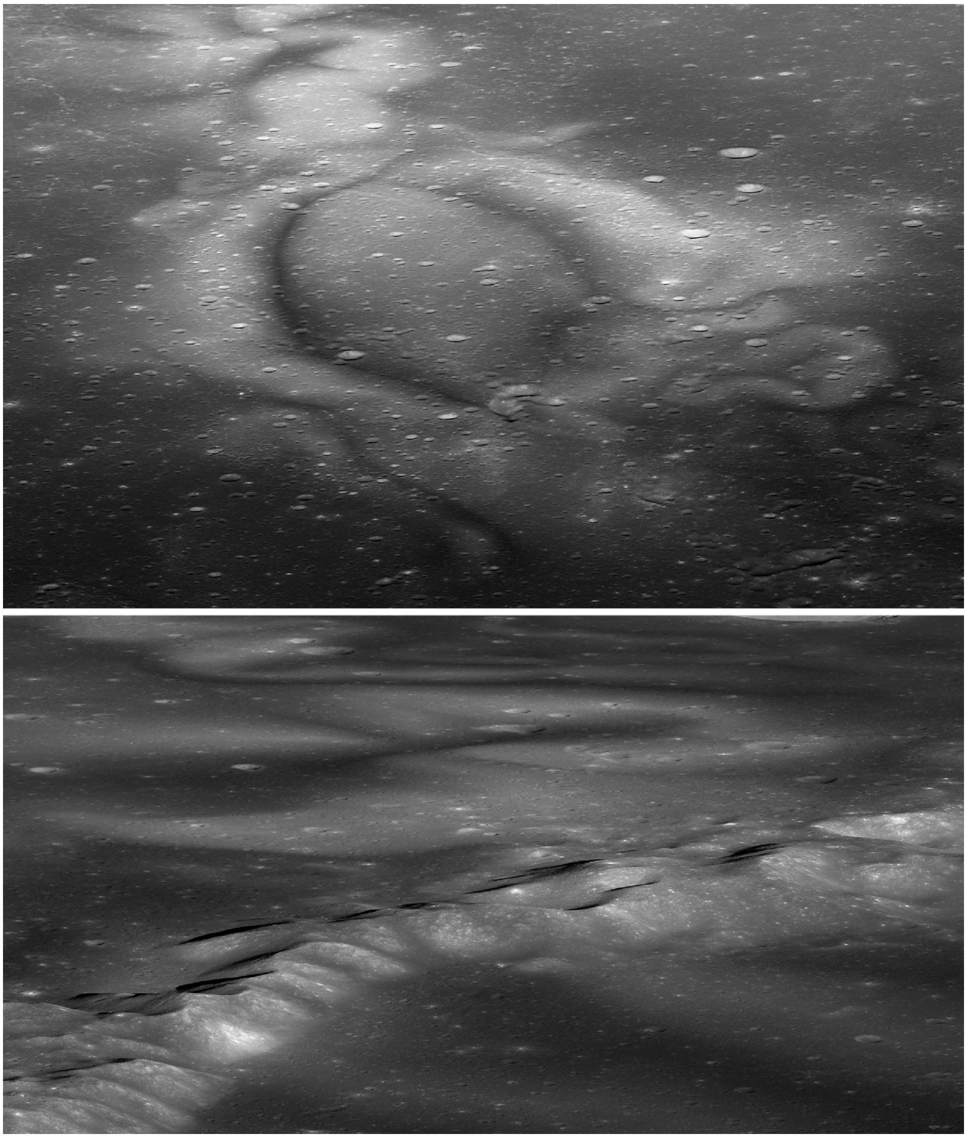

Fig. 1. Oblique views of swirls from the Lunar Reconnaissance Orbiter Camera Narrow Angle Camera (NAC). Top: Reiner Gamma seen from the west looking east, NAC image M1127569280L,R. Bottom: Mare Ingenii swirl seen from the east looking west, NAC images M191830503L,R. Both images are ~60 km wide at center.

These spectral properties are consistent with materials that have experienced less space weathering than typical lunar soils. Space weathering is the collection of physical (comminution, vitrification, agglutination) and chemical (reduction of ferrous iron to iron metal) changes that result from micrometeoroid bombardment and interactions with the solar wind (e.g., Hapke, 2001). Thus if the swirls are indeed immature (have experienced low degrees of space weathering), they must have either formed recently or have avoided the typical space weathering processes. These two scenarios lead to two formation models: swirls formed recently, due to cometary impacts (Schultz and Srnka, 1980; Bell and Hawke, 1987; Pinet et al., 2000; Starukhina and Shkuratov, 2004; Bruck Syal and Schultz, 2015) or swirls avoided the typical space weathering process, due to magnetic shielding from the solar wind (Hood and Schubert, 1980; Hood and Williams, 1989; Kramer et al., 2011b; Glotch et al., 2015).

In the comet impact model, the high-reflectance of swirls is due to recent scouring of the surface by large amounts of vapor generated by the extremely high-velocity nucleus impact, as well as scouring from impacting dust and ice particles from the inner coma (Schultz and Srnka, 1980; Bruck Syal and Schultz, 2015). The scouring is proposed to expose fresh regolith or to result in the compaction of regolith (or both), and the turbulence of the gas flow over the surface produces the distinctive swirl shapes. The local magnetic anomalies in this case are thought to result from magnetization of hot material in a transient magnetic field created by compression of the comet's intrinsic magnetic field (Gold and Soter, 1976; Schultz and Srnka, 1980; Bruck Syal and Schultz, 2015) or charge separation between plasma and ejecta (Crawford and Schultz, 1999; Bruck Syal and Schultz, 2015). Swirls at Reiner Gamma and Mare Marginis have unusual photometric properties; they are more forward scattering than other high-reflectance deposits such as crater ejecta. The enhanced forward scattering is thought to indicate lower millimeter-scale roughness and greater compaction of the regolith (Schultz and Srnka, 1980; Pinet et al., 2000; Kreslavsky and Shkuratov, 2003; Kaydash et al., 2009), which could be explained by the scouring from the comet impact. However, the thermophysical properties of the swirls are nearly identical to those of their surroundings, inconsistent with roughness or compaction differences (Glotch et al., 2015),