THE FORMATION OF LUNAR SWIRLS: INTERNATIONAL INVESTIGATIONS REACH CONSENSUS.
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Introduction: Lunar swirls are high albedo, curvilinear surface features, the origin of which has remained elusive ever since they were first identified [1]. From the collection of measurements over the past 40 years, we know the swirls to be: 1) optically bright; 2) spectrally immature across the UV-VIS-NIR; 3) associated with magnetic anomalies (although swirls have not been detected at all magnetic anomalies).

There are 3 hypotheses for swirl formation: (1) fresh exposures from a recent comet impact [2]; (2) isolated regions where the magnetic fields have spared the surfaces from the effects of space weathering [3]; and (3) electromagnetic transport and accumulation of the finest fraction of the lunar soil [4]. The results from international collaboration using new as well as older data are converging on a single model for swirl formation.

Electromagnetic Field: The Surface Vector Mapping (SVM) method, developed [5], combines global magnetic field data from *Lunar Prospector's Electron Reflectometer* and *Magnetometer,* and *Kaguya's Magnetometer*. When compared with high albedo markings at several magnetic anomalies such as the Reiner Gamma anomalies, three-dimensional structures of the magnetic field on/near the surface are well correlated with high albedo areas. Their results support the solar wind standoff model [6]. However, recent results from Kaguya's *Plasma energy Angle and Composition Experiment* reports that electrons are trapped in closed field lines of the magnetic anomaly and also electrons from the magnetic anomalies on the night side [7], supporting the existence of local electrostatic fields resulting from solar wind interaction with the magnetic anomalies.

Measurements of the surface-origin energetic neutral atoms by Chandrayaan-1's *Energetics Neutron Analyzer* of the *Sub-keV Atom Reflecting Analyzer* has been used to determine how much solar wind is reaching the surface at the magnetic anomalies. For example, initial analysis [8] showed that a strong magnetic anomaly reflects solar wind protons, and that the solar wind flux below the magnetic anomaly is lower by half.

Electromagnetic Spectrum: *Lunar Reconnaissance Orbiter's (LRO) Mini-RF* synthetic aperture radar on LRO provided a comprehensive set of X- (4.2 cm) and S-Band (12.6 cm) radar images of the lunar swirls, including the first radar observations of swirls on the farside of the Moon [16]. Swirls imaged with Mini-RF are indistinguishable from the surrounding regolith in both total radar backscatter and circular polarization ratio. This implies that average cm-scale roughness within the high-albedo portions of the swirls do not differ appreciably from the surroundings, and that the high optical reflectance of the swirls is related to a very thin surface phenomenon (<1 cm).

Three of *LRO's Diviner Radiometer* spectral channels are near 8 μm, and were selected to estimate the wavelength of the Christiansen feature, which is sensitive to the bulk silicate mineralogy of the surface. Analysis of swirl regions shows an anomaly in the position of the silicate Christiansen Feature consistent with reduced space weathering [8]. In addition, these data show that swirl regions are not thermophysically anomalous, which strongly constrains their formation mechanism. The conclusion from this study [8] supports the hypothesis that the swirls are formed as a result of deflection of the solar wind by local magnetic fields.

Chandrayaan-1's Moon Mineralogy Mapper were used to demonstrate that swirls surfaces do not mature at the same rate as regions away from magnetic anomalies [10]. In addition, maps derived from M^3 data that depicts the relative OH abundance (using the depth of the 2.82 μm absorption feature) showed that the swirls are depleted in OH compared with their surroundings [10]. This is further support for the hypothesis of that the magnetic (or induced electric) field is shielding the swirls from solar wind protons.

LRO's Wide Angle Camera color data consists of 7 channels that span the UV to visible. These data have been used [11,12] to demonstrate the unique detection quality of swirls in UV wavelengths. Even when swirls have only moderately elevated reflectance, or are often barely distinguishable in OMAT, band depth, or other spectral parameters, lunar swirls are clearly observable in 321/415 nm ratios. Far UV observations of swirls from *LRO's Lyman Alpha Mapping Project* provided further evidence that swirls in both highlands and mare regions are spectrally relatively red (or less blue) than surrounding terrains, indicating a difference in weathering in the swirls vs. non-swirl regions. Although [13] concluded that swirl spectra exhibit a characteristic red spectrum at wavelengths > ~160 nm, which is also consistent with greater abundances of feldspathic material, we argue that when all the data are considered, it is only the solar wind shielding model that remains.

References: [1] El Baz. (1971) *Trans. Amer. Geophys. Union 52*. [2] Schultz & Srnka (1980) *Nature 284*. [3] Hood & Schubert (1980) *Science 208*. [4] Garrick-Bethell et al. (2011) *Icarus 212*. [5] Tsunakawa H. et al. (2014) *Icarus 228*. [6] Tsunakawa H. (2015) *JGR 120*. [7] Nishino M. N. (2015) *Icarus 250*. [8] Wieser et al. (2010) *Geophys. Res. Lett., 37*. [9] Glotch T. D. et al. (2015) *Nat. Comm. 6*. [10] Kramer et al. (2011) *JGR 116*. [11] Denevi et al. (2014) *JGR 119*. [12] D e n e v i B. W. (2016) *Icarus,* 10.1016/j.icarus.2016.01.017. [13] Hendrix A. R. et al. (2016) *Icarus,* 10.1016/j.icarus.2016.01.003.