APPLICATIONS OF SOLAR WIND PARTICLE IMPACT SIMULATIONS AT LUNAR MAGNETIC ANOMALIES TO THE STUDY OF LUNAR SWIRLS.

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Introduction: Lunar swirls are high albedo features that exhibit low spectral maturity. They have been identified at various sites on the Moon, and all coincide with a lunar magnetic anomaly (magnomaly) [1], although not all magnomalies have an identifiable swirl. The leading hypothesis for lunar swirl origin is presented in [2] as magnetic field standoff of the solar wind which causes uneven space weathering at the swirl surface. This hypothesis fails to explain why lunar swirls are observed at some but not all of the magnetic anomalies present on the Moon. To investigate the solar wind standoff hypothesis further and to improve swirl mapping methodology, we map the lunar swirls at Mare Marginis and NW of Apollo basin using multispectral data and use particle tracking simulations [3] as a supplementary tool. We present the implications that our work has for potentially undetected swirls at known magnomalies.

Mapping Marginis: The initial mapping of swirls at Mare Marginis utilized data from the Lunar Reconnaissance Orbiter (LRO) Wide Angled Camera (WAC), LRO Global Lunar Digital terrain model 100 m (GLD100) [4] topography, Kaguya Multiband Imager (MI) [6], Clementine color-ratio [7] and optical maturity (OMAT) [8]. LRO Narrow Angle Camera (NAC) [5] imagery was used to outline the swirls at Marginis in detail.

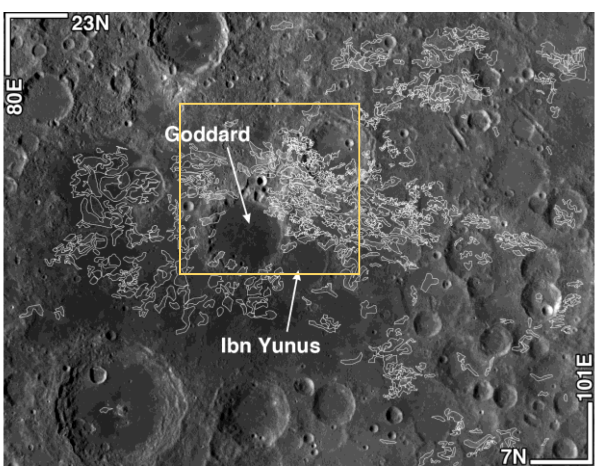

Figure 1. LRO WAC map for Mare Marginis with swirls outlined. Yellow box delineates boundary of images in Figure 2.

Mapping Apollo: The swirls NW of Apollo are challenging to map because the bright, heavily cratered highlands often appear to have swirl-like anomalies due to their complicated topography. To mitigate this, we generated a slope map from the WAC GLD100 (SLP), which we overlayed with the WAC 643 nm normalized reflectance image to distinguish high albedo swirls from high albedo slopes. Even so, after one pass of the region, only about half of the swirls could be detected with this method alone. The remaining half were found after using particle simulations as a guide.

Solar wind particle tracking simulations: We used the 2D solar wind particle tracking simulation presented in [2]. These simulations have shown previously that magnomalies at Mare Ingenii, Reiner Gamma, and Gerasimovich are sufficient to deflect incoming solar wind charged particles [3]. The simulations cannot resolve individual swirl features, but local minima in proton density and flux tend to coincide with regions of maximum swirl formation [3].

Discussion: Mare Marginis was used as a control for this investigation because of its bright and relatively easily discernible swirls. Our map agrees with previous results [3], showing that regions of elevated proton flux are lacking in swirls, while regions of minimum proton flux are rich in swirls. Locations of significant interest are the Goddard and Ibn Yunus basins in the center of the study region (Fig. 1). The model predicts a high proton flux across both mare-filled basins (Fig. 2c), and this is consistent with a conspicuous lack of swirls within the basins (Fig. 2a). The higher flux of protons coupled with the higher FeO content of the basalts causes the soils to more quickly weather to nanophase iron. This effect is observable in the OMAT parameter where Goddard and Ibn Yunus appear dark (i.e. mature), while the surrounding highlands appear brighter and contain swirls (Fig. 2b). The ejecta blanket of Goddard A crater highlights this effect because it can be traced into both basins and also into the surrounding highlands. The clear OMAT difference in basin vs highlands also exists within the Goddard A ejecta, which is evidence for uneven soil weathering at a magnomaly, a prediction made by the magnetic field standoff hypothesis [1].

Applications to Apollo: We applied the same simulations to NW of Apollo (Fig. 3). Again, the previously mapped swirls consistently appeared in regions of decreased proton flux. Identifying swirls in this region proved difficult owing to the complex topography. We used the proton flux map to tar-

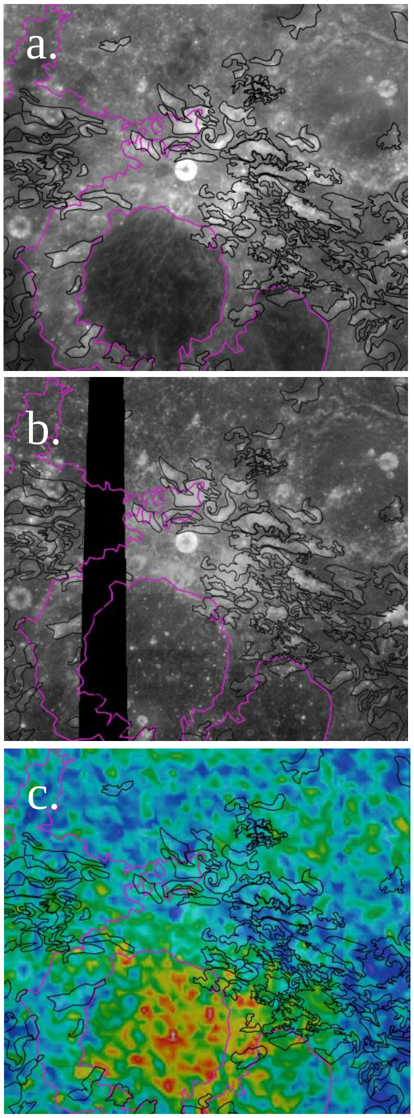

Figure 2. (a) LRO WAC 643 nm normalized reflectance, (b) Clementine OMAT, and (c) particle simulation proton flux map of region centered on Goddard A crater (see Fig. 1 for context). Pink outline denotes extent of mare basalts in Marginis (south). We note the conspicuous lack of swirls and increased optical maturity in regions of increased proton flux, particularly in the Goddard and Ibn Yunus basins.

get other regions of decreased proton flux in search of swirls. This targeted search doubled our swirl count at NW of Apollo, pointing to several faint lunar swirls that had been overlooked by our previous mapping techniques (Fig. 3).

Conclusion and Future Work: Preliminary analyses of the Mare Marginis and NW of Apollo magnomalies indicate that regions of swirl formation can be predicted by solar wind particle simulations. The inverse relationship between abundance of swirls and proton flux is in agreement with the magnetic shielding model for lunar swirl formation. The mapping of the NW of Apollo region was enhanced by our particle simulations, a technique which we will use to map lunar swirls at other magnomalies in future work. These particle simulations will be instrumental in the future study of lunar swirls as they will either assist in locating elusive swirls or allow us to say for certain that there are magnomalies where no lunar swirls exist.

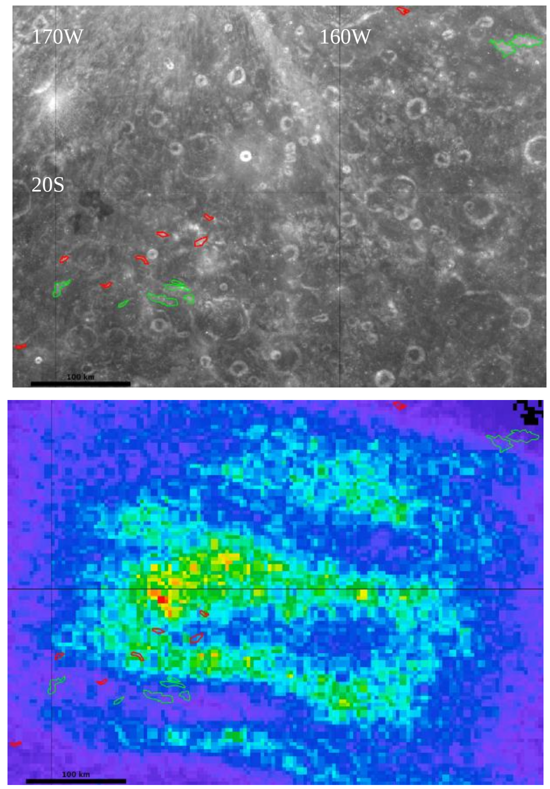

Figure 3. LRO WAC 643 reflectance (top), proton flux map (bottom) of NW of Apollo region. Swirls outlined in green were identified using multiple remote sensing data sets. Swirls outlined in red are faint and were identified using the particle simulations to target low-flux regions.

References: [1] Hood L. L. and Williams C. R. (1989) *LPSC XIX*, 99–113. [2] Hood L. L. and Schubert G. (1980) *Science*, 208, 49–51. [3] Harnett E. M. and Kramer G. Y. (2014) *LPSC XLV* Abstract #1777. [4] Scholten F. et al. (2012) *JGR*, 117. [5] Robinson, M. S. et al. (2010) *Space*, 150, 81–124. [6] Ohtake M. et al. (2008) *Space*, 42, 301–304. [7] McEwen A. S. et al. (1994) *Science*, 266, 1858– 1862. [8] Lucey P. G. et al. (2000) *JGR 105*, 20,377-20.386.