THE WIDENING DISTRIBUTION AND EXTENT OF LUNAR SWIRLS AS OBSERVED BY LAMP.

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Introduction: The sinuous lunar surficial features known as 'swirls' are amongst the most intriguing regions on the surface of the Moon. Several hypotheses for their formation have been put forward and include 1) magnetic shielding from solar wind [2], 2) cometary or meteorite swarm scouring of the shallow regolith [3-5], or 3) electromagnetic charge induced levitation and sorting of lunar dust [6, 7].

Three initial examinations of swirls have been performed in the ultraviolet (UV) [1, 8, 9], each one examined shorter wavelengths. Denevi et al. [1] mapped out swirls in the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) near-UV (NUV), observing that the most distinguishing characteristic of swirls in this wavelength region is a low 321/415 nm ratio coupled with moderate to high 415 nm reflectance. This methodology appears effective for differentiating swirls even within areas of high albedo. Hendrix et al. [8] also detailed examinations of the Reiner Gamma and Gerasimovich swirls using Lyman Alpha Mapping Project (LAMP) wavelengths >130 nm, noting swirls to be characterized by reddened FUV spectra. They also demonstrate that immature regolith becomes brighter (i.e., bluer) with exposure to space weathering. Denevi et al. [1] further note that some swirls cannot be discerned in the optical maturity index (OMAT) or band-depth images. Finally, in a precursor to the work presented here, Cahill et al. [9], examined LAMP global Lyman-α (Ly-α) albedo (121.6 nm) maps and noted FUV evidence consisting of low albedo for swirls coincident with regions noted by Denevi et al. [1] as well as in previously undocumented areas.

Herein we take the next steps leveraging the unique viewing geometry and wavelength range LAMP observes at night to first comprehensively map lunar swirls as observed in the FUV. Secondly, we compare our observations with previous work in order to detail what can and cannot be observed in the FUV relative the NUV, and vice versa.

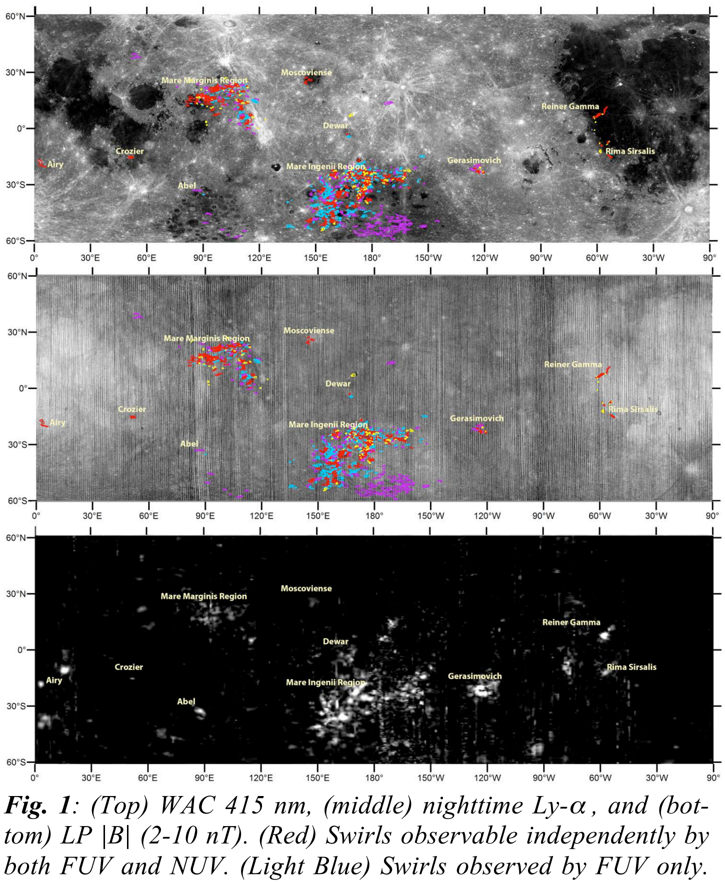

Fig. 1: (Top) WAC 415 nm, (middle) nighttime Ly-α, and (bottom) LP |B| (2-10 nT). (Red) Swirls observable independently by both FUV and NUV. (Light Blue) Swirls observed by FUV only. (Yellow) NUV identified [1] and confirmed in FUV. (Purple) Plausible LAMP-identified swirls near weak magnetic anomalies.

Data Sets: LAMP continues to provide insights into the upper ~100 nm of the regolith. LAMP is a FUV (57-196 nm) pushbroom photon-counting imaging spectrograph [10]. LAMP has also routinely collected both day and nighttime data of both polar and equatorial regions of the Moon. Here, global nighttime Lyman-α (Ly-α; 121.6 nm) normal albedo data are examined for low-albedo features as they relate to the detection and mapping of lunar swirls (**Fig. 1**). This data set is unique in comparison to all other LRO data sets in that it collects naturally reflected light at night of surfaces diffusely lit by solar Ly-α scattered off of interplanetary H atoms from all directions. This is a simplification, of course, as the Ly-α skyglow intensity varies with respect to the motion of the solar system and point sources from UV-bright stars, which are more plentiful in the southern hemisphere owing to the Galactic plane [10, 11]. As a result, the signal-to-noise of the LAMP nighttime data varies with latitude, increasing from north to south. Other maps analyzed include the LROC WAC color [12, 13] and Lunar Prospector (LP) fluxgate magnetometer [14] data.

Swirls… Low-Albedo?: Indeed, unlike the NUV and visible where lunar swirls are

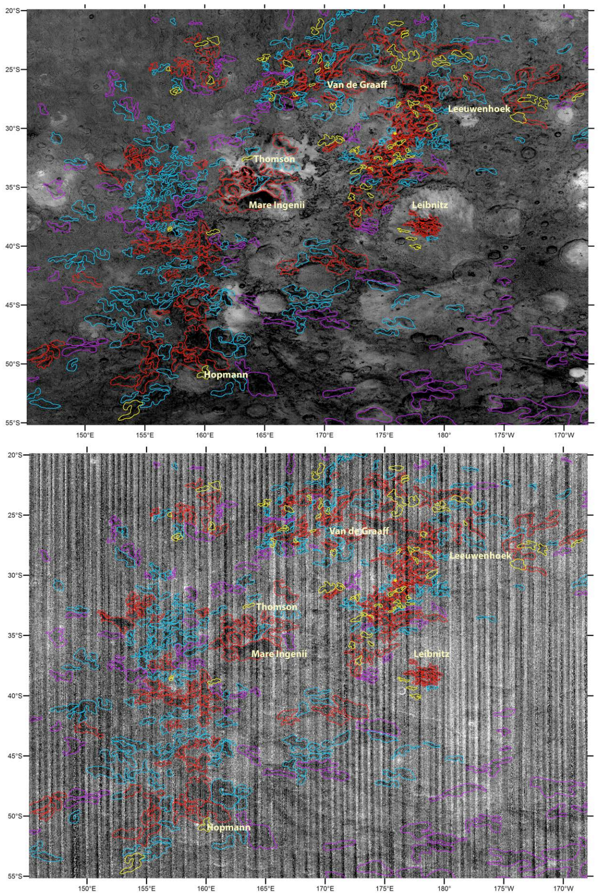

***Fig. 2**: Swirls mapped over western SPA (Top) nighttime Ly-α with swirls mapped, (Bottom) WAC 321/415 nm.*

known to show high reflectance relative to their surroundings, in Ly-α they have low albedo due to changes in material optical properties below ~180 nm.

Mapping Methodology: LAMP global Ly-α albedo maps were surveyed for low-albedo features with sinuous 'swirl-like' characteristics. During this process a WAC 415 nm reflectance mosaic was used for regional context. To maintain an initial independent LAMP assessment, this initial step was taken without referring to swirl boundary maps detailed by *Denevi et al.* [1] or LP magnetic anomaly maps [14]. Once low-albedo regions were identified, they were compared to LP magnetic anomaly maps as well as WAC color composite maps. This resulted in four classes of low-albedo features, shown in **Fig. 1 and 2**: 1) Independently verified, (in red; i.e., regions identified independently by both FUV and NUV surveys, respectively), 2) Ly-α identified (in light blue; i.e., only observed in the 121.6 nm band), 3) NUV identified/FUV confirmed (in yellow; i.e., swirls not initially noticed in the initial FUV survey, but documented by Denevi et al. [1] and subsequently confirmed in Ly-α), and 4) Plausible swirls (in purple; i.e., low-albedo features with an ambiguous morphology or setting and associated with weaker magnetic strength anomalies).

Observations & Discussion: Consistent with Denevi et al. [1], swirls are detected in LAMP Ly-α in the regions of Reiner Gamma, Mare Marginis, Rima Sirsalis, Crozier, Airy, Gerasimovich, Dewar, and South Pole-Aitken basin (**Fig. 1 & 2**). Swirls have previously been identified in all of these regions, however Ly-α often shows boundaries encompassing NUV and visible boundaries and often also show additional nearby sinuous low-albedo regions, swirls, not previously identified. That said, there are numerous areas with swirls that go initially unseen in Ly-α. Some of these (shown in yellow) are subsequently identified with additional NUV or magnetic data context, others are not. An analysis of these regions shows they have lower Ly-α albedo and higher magnetism values on average relative to their surroundings (**Fig. 3**). Swirl regions denoted by Denevi et al. [1] are consistent with these characteristics. Interestingly, low-albedo regions denoted as 'Plausible swirls' while showing similar average Ly-α values as swirls identified with high certainty, have lower values of total magnetic field strength (but higher magnetic field strength than 'off swirl' regional analyses).

References: [1] Denevi B. et al. (2016) Icarus, j.icarus.2016.01.017. [2] Hood L. et al. (1980) Science, 208, 49. [3] Schultz P. et al. (1980) Nature, 284, 22. [4] Le Mouélic S. et al. (2000) JGR, 105, 9445. [5] Syal M. et al. (2015) Icarus, 257, 194. [6] Pieters C. et al. (2014) LPSC, 45, 1408. [7] Garrick-Bethell I. et al. (2011) Icarus, 167, 136. [8] Hendrix A. et al. (2016) Icarus, 273, 68. [9] Cahill J. et al. (2016) LPSC, 47. [10] Gladstone R. et al. (2012) JGR, 117, doi:10.1029/2011JE003913. [11] Pryor W. et al. (1992) AJ, 394, 363-377. [12] Sato H. et al. (2014) JGR, 119, 1775. [13] Boyd A. et al. (2012) LPSC, 43, 2795. [14] Purucker M. et al. (2010) JGR, 115.

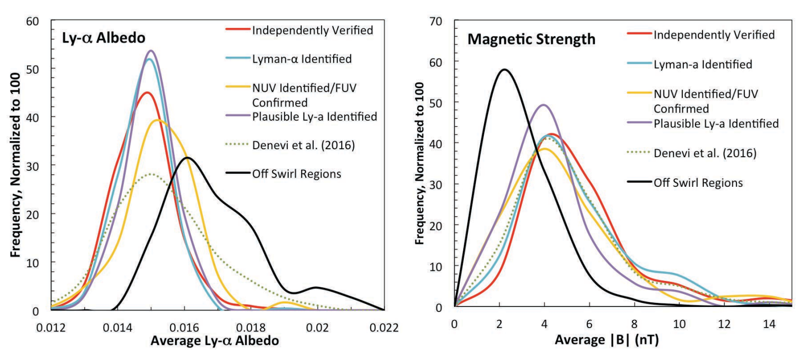

***Fig. 3**: Histograms of swirl characteristics detailing (Left) Ly-α, and (Right) total magnetism |B|. (Dotted) Study of Denevi et al. [1] mapped swirl regions. (Black) Regions nearby, but off swirl regions.*