FAR-ULTRAVIOLET MAPPING OF LUNAR SWIRLS AND OTHER ENIGMATIC LOW-ALBEDO FEATURES.
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Introduction: The Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP) has provided insights into the upper ~100 nm of the regolith, specifically detecting surface frost and estimating porosity of lunar polar regions in the far-ultraviolet (FUV) [1-3]. LAMP has also routinely collected both day and nighttime data of both polar and equatorial regions of the Moon. However, until recently, lunar non-polar FUV mapping studies have been of secondary priority due, in part, to the predominant brightness of starlight impinging upon the southern hemisphere during nighttime observations, as well as current instrument aperture configurations necessitating pinhole observations during the day. However, intial gaps and gores in the equatorial data resulting from these limitations are now filled in with repeated coverage and improved signal to noise ratios available after the accumulation of several years of operation. Initial efforts to examine these non-polar data have studied latitudinal variations in hydration as well as the examination of some swirls [6, 7]. Here, we build upon these works by mapping out low-albedo features, both understood and enigmatic, in the Lyman-α band.

Data Sets: LAMP is a FUV push-broom photon-counting imaging spectrograph collecting data in the 57-196 nm spectral range [1]. Here, global nighttime Lyman-α (Ly-α; 121.6 nm) normal albedo data are examined for low-albedo features as they are related to lunar regolith maturity (**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 theoretically 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 [1, 8]. 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 [9, 10], Mini-RF radar [11], and Lunar Prospector fluxgate magnetometer [12] data.

Low-Albedo Features: Many of the interesting low-albedo features observed in Ly-α include crater rays [5], pyroclastic deposits, and swirls (**Fig. 1**). We concentrate our examination on more enigmatic lunar features including swirls, normally associated with magnetic anomalies, and some low-albedo deposits that have no corresponding magnetic signatures.

Two initial examinations of swirls have been performed in the UV [4, 7]. Denevi et al. [4] mapped out swirls in the LROC WAC near-UV (NUV) observing that the most distinguishing characteristic of swirls in this region is a low 321/415 nm ratio coupled with moderate to high reflectance. This methodology appears most effective, differentiating swirls even within areas of uniformly high albedo. Hendrix et al. [7] also detailed examinations of the Reiner Gamma and Gerasimovich swirls using LAMP wavelengths >130 nm noting swirls to be characterized by reddened FUV

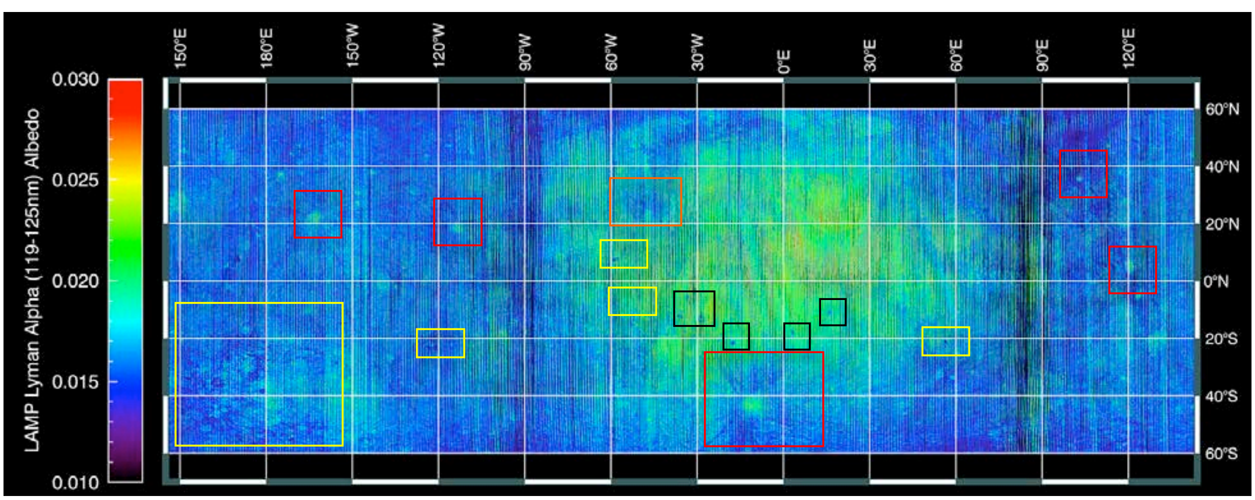

Fig. 1*: Lunar global non-polar nighttime Ly-α observations (30 ppd). (Black boxes) Enigmatic low Ly-α albedo features. (Yellow boxes) Observed lunar swirls. (Orange boxes) Discernable pyroclastic deposits. (Red boxes) Craters with high Ly-α albedo proximal ejecta and contrastingly low Ly-α albedo rays [5]. When constructing these preliminary albedo maps, the number of Δλ bins was divided, lowering the color bar values by a factor of three.*

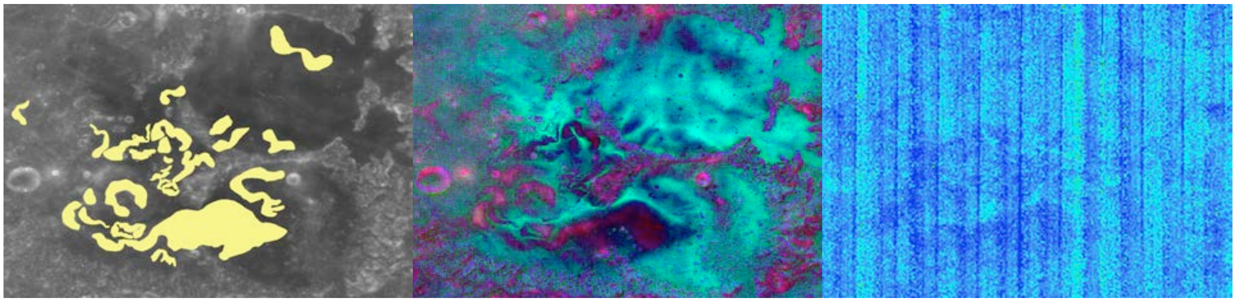

Fig. 2: SPA crater Thomson observed in (left) WAC 415 nm (400 mpp), (Middle) WAC Color R-415, G-321/415, B- 321/360 nm; and (Right) nighttime Ly-α (32 ppd) albedo observations. Yellow regions defined by [4].

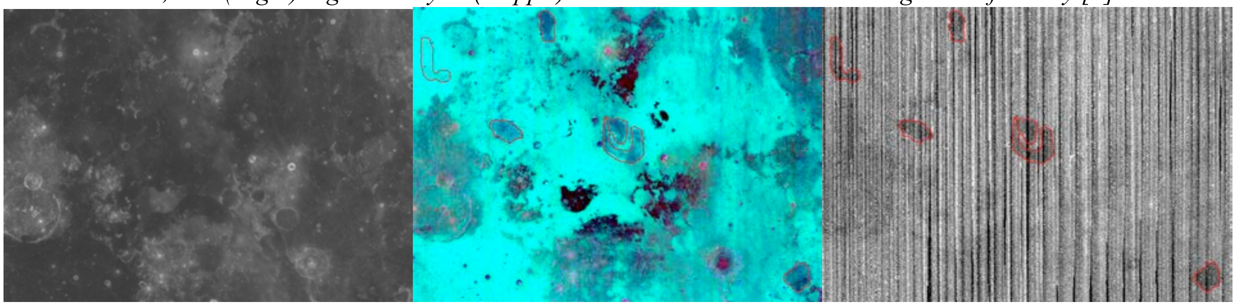

Fig. 3: (Left) WAC 415 nm reflectance of Oceanus Procellarum/Mare Nubium; (Middle) WAC Color R-415 nm, G-321/415nm, B- 321/360nm; (Right) Non-polar nighttime Ly-α observations. (Red outlines) Denote enigmatic low albedo features observed in Ly-α, and observed to varying degrees in WAC color data.

albedos and noting that immature regolith becomes brighter (i.e., bluer) with exposure. Denevi et al. [4] further note that some swirls cannot be discerned in OMAT or band-depth images. Herein lies the impetus of this study; to see if the unique viewing geometry and wavelengths LAMP observes offer additional complementary or unique details about the lunar surface other instruments cannot.

Observations and Discussion: Initial analyses of non-polar LAMP nighttime observations show familiar discrimination of highland (lower Ly-α albedo) and mare (higher Ly-α albedo) regions with relative ease albeit with inverted albedo characteristics to NUV, VIS, and NIR data sets (**Fig. 1**). LAMP also distinguishes swirls relatively well, but in most cases ease of discernment increases moving to lower latitudes. For example, swirls in Moscoviense are not detectable, while swirls in Marginis, Rima Sirsalis, and Crozier regions, while detectable, show less spatial definition making it more difficult to document their spatial extent. Reiner Gamma is visible in Ly-α and some internal characteristics are discernable; Airy is also detectable, but has differing boundaries relative to the WAC.

Moving to the southern hemisphere, in and around SPA, swirls are more distinguishable in the Ly-α band (**Fig. 1**). SPA in particular shows swirls with relatively well defined boundaries consistent with mapped swirl regions defined by Denevi et al. [4] using WAC color (**Fig. 2**). That said, a particularly difficult area mapped in great detail by Denevi et al. [4], is a mountainous area between Birkeland and Leeuwenhoek crater. In Ly-α, it is obvious there is spatial structure within this region, but it is so intricate it is difficult to discern swirls in a similar fashion to WAC color data. A further challenge is distinguishing low albedo characteristics of crater rays from swirls. Developing a methodology to do this within the LAMP data set is ongoing.

Other Low Ly-α Albedo Features: Also observed, primarily on the lunar nearside, are several discrete low Ly-α albedo features (**Fig. 3**). These are unique within their region of the data being the only features to crisply stand out in Ly-α. Interestingly, some of these can be observed in LROC WAC color data using an RGB color stretch featured by [4, 13] while others cannot (**Fig. 3**). Most do not appear to correlate with a rise or fall in topography, are not observed in Mini-RF S-band data, but do have relatively higher reflectance in WAC color. They also do not exhibit the wispy geomorphology of swirls and are not associated with LP observed magnetic anomalies.

References: [1] Gladstone et al. (2012) JGR, 117, 1. [2] Hayne et al. (2015) Icarus, 255, 68. [3] Mandt et al. (2015) Icarus, in press. [4] Denevi et al. (2015) Icarus, in press. [5] Stickle et al. (2016) LPSC. [6] Hendrix et al. (2012) JGR, 117. [7] Hendrix et al. (2016) Icarus, in press. [8] Pryor et al. (1992) AJ, 394, 363. [9] Sato et al. (2014) JGR, 119, 1775-1805. [10] Boyd et al. (2012) LPSC, 43, 2795. [11] Nozette et al. (2010) SSR, 150, 285. [12] Purucker and Nicholas (2010) JGR, 115. [13] Denevi B.W. et al. (2014) JGR, 119, 976.