SENSING DIURNAL HYDROGENATION OF LUNAR REGOLITH USING PROTON RADIATION FROM THE MOON. N. A. Schwadron, J. K. Wilson[1], A. P. Jordan[1], M. D. Looper[2], C. Zeitlin[3], L. W. Townsend[4], H. E. Spence[1], J. Legere[1], P. Bloser[1], W. Farrell[5], D. Hurley[6], N. E. Petro[5], T. J. Stubbs[5], C. Pieters[7], Y. Iwata[8], [1]Space Science Center, University of New Hampshire, Durham, NH (nschwadron@unh.edu), [2]The Aerospace Corporation, Los Angeles, CA, [3]Leidos, Houston, Texas, [4]Dept. of Nuclear Engineering, Univ. of Tennessee, Knoxville, TN, [5]NASA Goddard Space Flight Center, Greenbelt, MD, [6]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, [7]Dept. of Earth Environmental and Planetary Science, Brown University, Providence, RI. [8]NIRS, 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan

Summary: Detection of proton radiation from the Moon offers a new observational method for mapping compositional variations over the lunar surface. Recently, it was discovered that the yield of proton radiation from the lunar regolith depends on latitude: the yield increases toward higher latitudes. This dependence was attributed to a surface layer of hydrogenated regolith near the poles. Here, an improved technique is applied to detect proton radiation from the lunar horizon and investigate diurnal variation in hydrogenation. Simulations show that (1) proton radiation yields on the horizon are enhanced compared to nadir; (2) hydrogenation enhancements in the upper several to 10 cm of regolith enhance proton radiation yields. CRaTER observes a significantly higher yield of protons from the lunar horizon compared to nadir, and a significantly higher yield on the morning terminator compared to the evening terminator. These results show the first evidence of the diurnal dependence of lunar hydrogenation based on observations of protons coming directly from the hydrogenated material in the lunar regolith, and pose significant challenges to models of the lunar hydrogenation cycle.

Introduction: For more than half a century there has been intense study of water on the Moon. The techniques employed rely on either detection of electromagnetic radiation or subatomic particles from the Moon and therefore probe regolith to different depths. The Moon Mineralogy Mapper (M^3) on Chandrayaan-1 detected 2.8 to 3.0 μm absorption features indicating the OH and H_2O in the upper (tens of microns) surface. The absorption was strongest at high latitudes and at several fresh feldspathic craters but was also distributed over regions well below 80° latitude (Pieters et al., 2009). Infrared (IR) measurements by the Deep Impact spacecraft (during Dec. 2007 and June 2009 lunar flybys) indicated that hydration was greatest near the terminators and least near the subsolar point, implying a diurnal cycle of dehydration and rehydration (Sunshine et al., 2009). Finally, nadir-pointed ultraviolet spectroscopy measurements by the Lyman-Alpha Mapping Project (LAMP) instrument on the Lunar Reconnaissance Orbiter (LRO) showed a local minimum in hydration at noon, increasing approximately symmetrically toward either terminator (Hendrix et al., 2012), further corroborating that surface hydration varies diurnally.

Supplementing IR and UV observations are measurements of subatomic particles released from the Moon by galactic cosmic ray (GCR) interactions within the regolith. The Lunar Exploration Neutron Detector (LEND) instrument on LRO, measures epithermal neutrons and has detected suppressions associated with permanently shadowed regions near the South Pole; these suppressions indicate elevated hydrogenation (which includes hydration) in the regolith down to ~50 cm and below.

GCRs also release protons from the lunar regolith. Previously, a new method involving measurement of high-energy (~10–100 MeV) protons from the moon by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on LRO showed that hydration at high latitudes is not vertically uniform within the regolith. Specifically, the CRaTER observations, which show an excess of protons from polar regions, are consistent with elevated hydration at the surface (Schwadron et al., 2016). The observation begs the question of the existence of a diurnal dependence in the protons emitted from this top hydrated layer.

Data and Reduction: Nominally the CRaTER instrument is directed toward the lunar surface, configured well to detect proton radiation from the Moon. During four periods in 2015 and 2016 when the polar orbit of LRO passed over the longitudes of Oceanus Procellarum, LRO was rotated to point CRaTER's field of view towards the lunar horizon. Wilson et al. (LPSC, 2017) provide details concerning CRaTER's observations and data reduction methods.

Key Observational Signatures: We observe four fundamental signatures indicating the physical properties of radiation interactions at the Moon and diurnal variation. The first two signatures below are associated with well-known cosmic ray physics:

- *Lunar Blockage* - GCR proton rates are reduced during periods when the instrument is directed toward the horizon. Analysis shows that this reduction in GCR rates is likely the effect of increased lunar blockage of incident GCR particles.
- *Cosmic Ray Anisotropy* - GCR proton rates are lower when viewing the AM terminator as com-

pared to the PM terminator. Analysis shows that this asymmetry is likely the result of the cosmic ray anisotropy.

The next two signatures indicate new results important for understanding lunar albedo proton radiation and its implications:

- *Increased Secondary Yields from Horizon* - Albedo proton yields are increased from the horizon as compared to nadir. GEANT4 simulations consistently show an increased flux of albedo protons from the horizon as compared to nadir. This is the result of viewing larger fluxes of collisional products (secondary and tertiary protons) produced in the shallow regolith.
- *Diurnal Variation in the Proton Radiation Albedo* - Albedo proton yields are significantly increased from the AM terminator as compared to the PM terminator. The effect is likely the result of increased hydrogenation on the AM terminator. The hydrogen enhancement in the upper ~10 cm layer of regolith is consistent with the neutron desiccation layer (Feldman et al., 1998), which should enhance the proton albedo but reduce the neutron albedo.

Discussion: The dawn/dusk asymmetry observed by CRaTER is large and must be caused by a change in interactions on nuclear energy scales. This change is most simply explained by an enrichment of hydrogen, whether molecular or atomic, because enhancing light nuclei like hydrogen fundamentally changes the nuclear interactions experienced by GCRs in the top ~10 cm of regolith (Schwadron et al., 2016).

To explain the CRaTER observations, the morning terminator needs a concentration of H that is significantly larger than at the evening terminator. At least the top ~1 mm of regolith on the dayside has a larger concentration of OH/H_2O (Clark, 2009). It is not clear how deep this layer extends. Apollo soil samples have H concentrations of ~10–100 ppm, and epithermal neutron measurements indicate the bulk concentration of H in the highlands has a similar range (Lawrence et al., 2015). These latter measurements, however, do not exclude a hydrogen-rich layer that is < 30 g cm^{-2} (Lawrence et al., 2011). Ambiguity exists because thin, hydrogenated layers increase the epithermal neutron flux. If there is a surficial layer that varies diurnally, it would have to be tens of cm thick to be detected with epithermal neutron data.

At the morning terminator, the surficial concentration of H_2O, and thus H, may be orders of magnitude greater than at the evening terminator (Schorghofer, 2014) because as H_2O moves from night to day, it enhances the concentration at the morning terminator. The concentration could be similar to that needed to explain CRaTER diurnal observations, though it depends on the depths to which CRaTER is most sensitive.

Two factors further increase the concentration of H we expect at the morning terminator. First, the evening terminator, being colder than mid-day longitudes, could have a higher concentration of H than the dayside. The dawn H enhancement leads to an even higher total H abundance. Second, the region we observed — mainly Oceanus Procellarum — likely contains an increased concentration of H (Feldman et al., 1991).

Simultaneous measurement of high-energy secondary neutrons along with the tertiary protons produced through collisions in the shallow regolith will allow for significant new insights into this relatively unexplored portion of the lunar surface. Application of a newly developed detector, Dose Spectra from Energetic Particles and Neutrons (DoSEN, Schwadron et al., 2013) would provide the measurements of neutrons needed to discern effects of hydration at high energies. Our results raise significant questions, such as how thick a hydrogenated layer can be while still able to vary on diurnal scales. Continuing analysis of laboratory results, remote sensing observations, and modeling will be critical in coming years as we continue the synthesis of observations involving UV, infrared, and epithermal neutron measurements in addition to the new technique of observing nadir and horizon emissions of proton radiation from the Moon. With nadir and horizon observations at targeted portions of the lunar surface, the CRaTER instrument is poised to illuminate the ~10 cm upper layer of hydrogenated regolith over local times from morning to evening on the lunar surface, promising new insights into the inventory of lunar hydrogen.

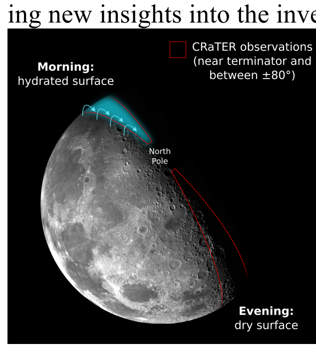

Figure 1. Strong enhancment of hydrogention observed from proton radiation by CRaTER suggests ongoing day-night migration of Hydrogenous species.

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