

## POSSIBLE ALBEDO PROTON SIGNATURE OF HYDRATED LUNAR SURFACE LAYER

N. A. Schwadron<sup>1</sup>, J. K. Wilson<sup>1</sup>, M. D. Looper<sup>2</sup>, A. Jordan<sup>1</sup>, H. E. Spence<sup>1</sup>, J. B. Blake<sup>2</sup>, A. W. Case<sup>3</sup>, Y. Iwata<sup>4</sup>, J. C. Kasper<sup>5,3</sup>, W. M. Farrell<sup>6</sup>, D. J. Lawrence<sup>7</sup>, G. Livadiotis<sup>8</sup>, J. Mazur<sup>2</sup>, N. Petro<sup>6</sup>, C. Pieters<sup>9</sup>, S. Smith<sup>1</sup>, L. W. Townsend<sup>10</sup>, C. Zeitlin<sup>11</sup>, <sup>1</sup>University of New Hampshire, Space Science Center and Inst. of Earth, Oceans and Space, Morse Hall, 8 College Rd, Durham, NH 03824, US, <sup>2</sup>The Aerospace Corporation, El Segundo, CA 90245-4609, USA, <sup>3</sup>High Energy Astrophysics Division, Harvard Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA, <sup>4</sup>NIRS, 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan, <sup>5</sup>Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI 48109-2143, USA, <sup>6</sup>Goddard Spaceflight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, <sup>7</sup>Johns Hopkins University, Applied Physics Laboratory, Laurel, MD 20723-6099, <sup>8</sup>Southwest Research Institute, Earth Oceans and Space Science, University of New Hampshire, Durham, NH, 03824, <sup>9</sup>Brown University, Planetary Geosciences Group, Dept of Earth Environmental and Planetary Sciences, 324 Brook St, Providence, Rhode Island, 02912, <sup>10</sup>University of Tennessee, Knoxville, TN, 37996, <sup>11</sup>Lockheed Martin Information Services & Global Solutions

**Introduction:** Volatile accumulation in permanently shaded regions (PSRs) at the lunar poles has been suggested for many years, starting before the Apollo era [1,2] and continuing well beyond it [e.g., 3]. The Lunar Prospector Neutron Spectrometer (LP-NS) utilized neutron spectroscopy to probe the lunar regolith down to depths of ~10-50 cm, specifically showing the high abundance of hydrogen (H) or hydrogenous species in PSRs where epithermal neutron emission is suppressed [4,5]. Similarly, the Lunar Exploration Neutron Detector (LEND) on the Lunar Reconnaissance Orbiter (LRO) has mapped lunar neutron fluxes [6], though the observations are subject to potential backgrounds that could degrade the resolution [7].

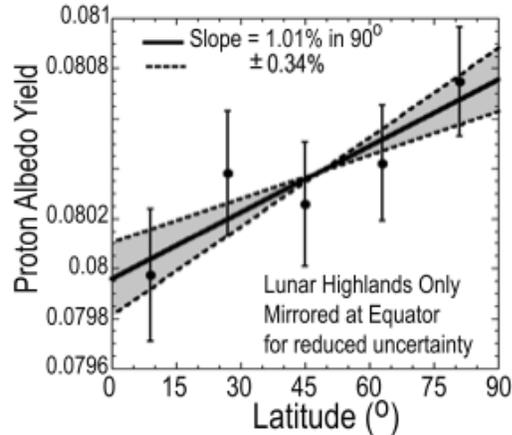
New infrared spectroscopic observations of the lunar surface provide unambiguous identification of OH and H<sub>2</sub>O [8, 9, 10]. For example, the Moon Mineralogy Mapper (M<sup>3</sup>) on Chandrayaan-1 detected absorption features in the wavelength range from 2.8 to 3.0  $\mu\text{m}$  indicating the presence of materials containing OH and H<sub>2</sub>O. There is a clear contrast between these spectral absorption measurements and the neutron spectrometer observations. Whereas the latter indicate pronounced deficits of albedo neutrons in polar PSRs, the absorption features observed by M<sup>3</sup> are far more widespread at high latitudes, extending well below 80° latitude. A key difference in these observations is that the M<sup>3</sup> absorption features originate from H in the upper surface (as thin as tens of microns). In contrast, the neutron data is sensitive to H from the surface down to ~50 cm in the regolith. These two observations suggest that there is a widespread thin veneer containing OH and H<sub>2</sub>O, whereas the deeper regolith is enriched in H mainly in PSRs that remain cold over 100's Myr. Water molecules residing in polar cold traps can be redistributed by ion sputtering or impact vaporization [11]. These ejected molecules could contribute to the water and OH veneer observed in 3  $\mu\text{m}$  absorption features outside of permanent shadow.

Here, we discuss a new technique for observing hydrated material at the Moon using the energetic proton albedo [12,13] measured by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter (LRO). Until recently, it was unclear how the energetic proton albedo could be used to infer compositional signatures of the regolith. This work [14] assembles laboratory measurements, simulations, and CRaTER observations to better understand the signatures and implications of the energetic proton albedo, specifically as they address the question of regolith volatile content and distribution.

**The CRaTER Proton Albedo Engima:** Both laboratory measurements and simulations confirm that the presence of H in the regolith should lead to a suppression of the proton albedo coming upward near the surface normal from the lunar regolith, which is the subset of albedo observed by CRaTER when LRO is in its nominal attitude [14]. There are two key physical mechanisms at work. Primary GCR ions penetrate the regolith and can excite heavy nuclei, leading to nuclear evaporation. Therefore, higher concentrations of heavy atoms should enhance the proton albedo. In contrast, the presence of higher concentrations of hydrogen should suppress the proton albedo through enhanced forward-directed interaction products and reduction of nuclear evaporation due to the lower average Z of hydrated material [14].

The lack of albedo particle production from collisions on hydrogen nuclei suggests that we should observe a pronounced latitude trend in which polar regions, which have higher concentrations of hydrogen, should show clear *reductions* in the proton albedo. To check this prediction, we formed latitudinal profiles of albedo proton data observed by CRaTER from the most recent albedo proton maps [15], which were corrected for altitude and background effects. The latitudinal trend from the highlands regolith generally shows an *enhancement* in albedo (Fig. 1) protons at high lati-

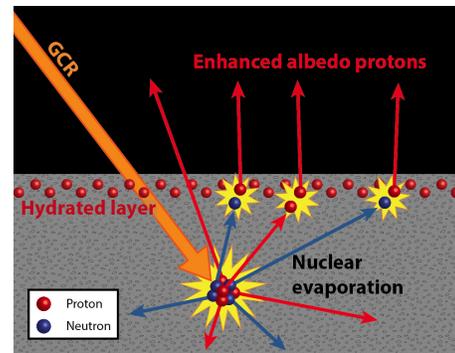
tudes, as opposed to the suppression expected from hydrogen-rich regions.



**Fig 1.** The latitude trend in the proton albedo. The solid line shows the fit slope using a  $\chi$ -square minimization and the dashed lines show the uncertainty limits.

We are left with a significant puzzle as to why the polar highlands show enhancements in the albedo proton flux where we expect to observe suppression due to higher abundances of hydrogen. While statistical uncertainties are a possible culprit, rebinning the albedo proton data fail to reveal any significant, systematic trend of suppression at high latitudes.

**Possible Resolution of the Enigma – Thin Hydrated Surface Layer:** Higher energy primary GCRs are less likely to interact with hydrogen near the top layer of regolith and more likely to interact with material deeper in the regolith (Fig. 2). The nuclear evaporation process from deep in the regolith produces abundant secondary particles in all directions. The highest flux of these secondary albedo particles moves up through the surface in the form of neutrons up to  $\sim 100$  MeV [13]. If an upward-traveling neutron collides with a hydrogen nucleus near the surface, the collision would yield an additional “tertiary” proton, to which energy up to the full neutron energy may be transferred. In general, the interaction of secondaries from deeper in the regolith with the hydrated layer could create an excess of albedo protons. Therefore, if the surface layer rich in hydrogen overlying material poorer in hydrogen is more prevalent at higher latitudes, then we should find a positive latitude gradient in albedo proton yields, as observed. This would solve the puzzle posed in the preceding section.



**Fig. 2.** Illustration of the effects of a hydrated layer of lunar regolith. In this case, higher energy primary GCRs are less likely to interact with hydrogen near the top layer of regolith and more likely to interact with material deeper in the regolith. The nuclear evaporation process from deep in the regolith produces abundant secondary neutrons of up to  $\sim 100$  MeV [13]. If a neutron collides with a hydrogen nucleus near the surface, the collision would yield an additional “tertiary” proton. In general, the interaction of secondaries from deeper in the regolith with the hydrated layer would create an excess of albedo protons.

**Summary:** We discuss here the implications of recent LRO/CRaTER observations of the proton albedo suggesting sensitivity to a thin (1-10 cm) hydrous layer near the surface. We collect laboratory measurements, observations, simulations and calculations that demonstrate why this scenario is an attractive explanation of the positive latitude gradient in the proton yield observed by CRaTER. We also discuss the plan for future observations to test this hypothesis and better resolve stratification of hydrated material on the moon.

**References:** [1] Urey, H. C. and Korff, S. A. (1952) *Physics Today*, 5, 1. [2] Watson, K. et al. (1961), *J. Geophys. Res.*, 66, 3033–3045. [3] Arnold, J. R (1979), *J. Geophys. Res.*, 84, 5659–5668. [4] Feldman, W. C. et al. (1998) *Science*, 281, 1496. [5] Lawrence, D. J. et al. (2006) *JGR Planets*, 111, E08001. [6] Litvik et al. (2012) *JGR Planets*, 117, E00H22. [7] Lawrence, D. J. et al. (2011) *JGR Planets*, 11, E01002. [8] Clark, R. N. (2009), *Science*, 326, 562. [9] Pieters, C. M. et al. (2009) *Science*, 326, 568. [10] J. Sunshine, J. M. et al. (2009) *Science*, 326, 565. [11] Farrell, W. M. et al. (2013) *PSS*, 89, 15-20. [12] Wilson, J. K., et al. (2012) *JGR Planets*, 117, E00H23. [13] Looper, M. D. et al. (2013), *Space Weather*, 11, 142–152. [14] Schwadron, N. A. et al. (2015), *Icarus*, Submitted. [15] Wilson, J. K. et al. (2015), *Icarus*, Submitted.