THE EFFECTS OF HYDROGENATED SURFACE LAYERS IN LUNAR REGOLITH ON GALACTIC COSMIC RAY INDUCED PROTON ALBEDO YIELDS.

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Introduction: The Lunar Reconnaissance Orbiter (LRO) spacecraft carries an instrument to study the galactic cosmic ray (GCR) environment in the lunar vicinity. This instrument, the Cosmic Ray Telescope for the Effects of Radiation (CRaTER), is composed of a stack of 6 silicon detectors, and is capable of detecting heavy charged particles in a wide range of kinetic energies. The GCR spectrum is composed of all naturally occurring heavy charged particles and is isotropic in direction for a given point in free space. After passing into the surface, GCR particles collide with stationary nuclei within the lunar bulk, creating secondary particles. The albedo proton spectrum observed by the CRaTER instrument contains directly reflected incident particles, as well as secondary particles that have escaped the lunar surface.

Schwadron et al. observe a 40% difference in the proton fluxes measured by the CRaTER instrument when facing the lunar limb vs. nadir, and also report that proton albedo flux is suppressed by a hydrogenated layer within the lunar regolith [1, 2]. This phenomenon allows for the use of variations in measured albedo proton flux as a method to study variations in water concentration within the regolith below [2]. In order to do so, however, a thorough understanding of the effects of surface hydrogen on albedo proton yield is necessary. In this work, we investigate the effects of surface hydrogen within lunar regolith on albedo proton spectra as a function of emission angle and hydrogenated layer thickness.

Radiation Transport Model: The interactions of GCR particles within three separate lunar regolith geometries have been modeled using the Monte Carlo Nuetral Particle (MCNP6) radiation transport code. In this model, an isotropic GCR spectrum comprised of elements ^{1}H through ^{56}Fe representative of a typical solar minimum is used as the boundary condition flux. In each case, the resulting albedo proton spectrum is tallied on the outer surface as a function of off-zenith angle. The binned tally fluxes are also corrected for solid angle. Since this study is concerned with albedo particles, particles crossing out of the regolith geometry through the incident surface are recorded. The tallied kinetic energy range, 60-400 MeV, is selected to be compatible with the observable range of the CRaTER instrument. The albedo proton yield from a reference geometry of dry regolith is compared with the results of regolith geometries containing 1 cm and 10 cm surface layers of water.

GCR Surrogate Source Term: The transport calculation was performed independently for each incident element to ensure converged statistics. The results from each element are weighted according to its relative abundance in the incident GCR spectrum and combined to form the final albedo yield spectrum. Ensuring converged statistics over 26 separate elements for each geometry, however, is computationally resource intensive. In this study, it is observed that the ^{1}H, ^{2}He, ^{12}C, ^{28}Si, ^{56}Fe components together serve as a sufficient surrogate for the entire GCR source term for the purposes of studying albedo yields in hydrogenated lunar regolith. The average difference for the 1 cm hydrogenated layer albedo flux between the full GCR source spectrum and the surrogate spectrum is 4.97%. For the 10 cm hydrogenated layer case, the difference is 5.08%.

Hydrogenated Layer Effects: The proton albedo fluxes as a function of emission for each of the three geometries are shown in Figure 1. For the dry regolith case, the albedo proton spectrum has a minimum value at 0º off-zenith, and a maximum value at 90º off-zenith. This behavior agrees with the increased albedo proton flux when observing the lunar limb. As expected, the presence of a hydrogenated layer in the lunar regolith did suppress the overall albedo proton spectrum considerably for most angles. However, at angles approximately less than 10º off-zenith, the proton albedo flux is

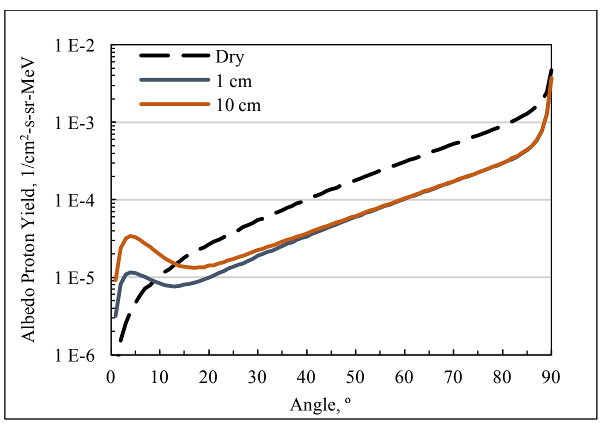

Figure 1. A comparison of the GCR induced albedo proton emission spectra as a function of off-zenith emission angle for dry regolith, 1 cm water, and 10 cm water.

larger in the presence of hydrogenated layers than for dry regolith. This enhancement is likely the result of protons within the hydrogenated layer being ejected from the regolith via elastic collisions with secondary neutrons produced deeper within the regolith, as illustrated in Figure 2. This explanation is supported by the observation that the enhancement becomes more exhaggerated as the thickness of the hydrogenated layer grows. The enhancement between the 10 cm and 1 cm cases in albedo proton flux for angles less than 10º off-zenith is roughly 190%. At angles larger than 40º off-zenith, the proton albedo spectra for both the 1 cm and 10 cm hydrogenated layer cases are within a few percent. Albedo proton suppression between the dry regolith case and both hydrogenated layer cases is roughly uniform at 66% between 40º off-zenith and 85º off-zenith, and decreases to value of 22% suppression at 90º off-zenith.

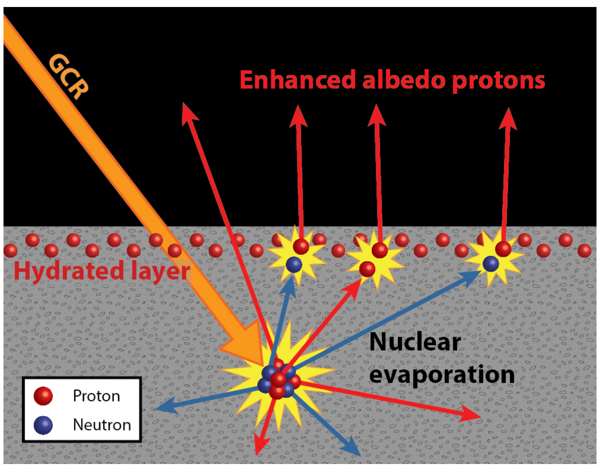

Figure 2. An illustration of the mechanism producing enhancements in albedo proton yields from a hydrogenated surface layer at near-zenith angles.

References:

[1] Schwadron, N. A. et al. (2016) *Icarus*, *273*, 25-35. [2] Schwadron, N. A., et al. (2016) *LPS XLVII*, Abstract #1583.