Lunar Albedo Protons and the Hunt for Subsurface Hydrogen

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Background

The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) has been monitoring the presence of galactic cosmic rays (GCR) in the local interplanetary space environment since the launch of the Lunar Reconnaissance Orbiter (LRO) in 2009. CRaTER is a charged-particle linear energy transfer (LET) spectrometer capable of observing the primary GCR spectrum, as well as lunar surface albedo radiation[1]. When the highly-energetic and heavy-charged particles comprising the GCR spectrum pass into the lunar bulk, a population of albedo protons is created via nuclear interactions within the regolith matter. These nuclear interactions include both elastic and inelastic processes, and the resulting albedo proton spectrum is a function of the incident GCR properties as well as the composition of the lunar regolith. Therefore, variations in lunar regolith composition are manifested as changes in the albedo proton spectrum observed by the CRaTER instrument[2,3]. In this work, we investigate how the presence and absence of subsurface hydrogen is expected to affect the albedo proton spectrum using the MCNP6 general purpose radiation transport code. Furthermore, we discuss how the observable population of albedo protons changes as a function of CRaTER's altitude, orientation, and detector coincidence.

Lunar Regolith Model

The spectrum of albedo protons being emitted from the lunar surface was calculated using the MCNP6 radiation transport code. The source term representing the incident galactic cosmic radiation (GCR) spectrum was constructed using the Badhwar-O'Neill 2014 model[4]. All GCR species from Z=1 to Z=28 were sampled in the source spectrum. Source particles were inserted isotropically upon the lunar surface. Wet regolith was modeled to have 9 surface layers (1 cm each) followed by a deep layer. The H concentration by weight was assumed be 1% in the top layer, increasing by 1% in each subsequent layer to reach 10% H concentration in the deep layer (see Figure 1). The resulting albedo proton spectrum exiting the lunar surface was tallied as a function of energy and angle from the surface normal. Figure 2 illustrates the resulting albedo spectra for dry and wet regolith binned as a function of surface emission angle for all energies. A more complete representation of the albedo proton spectrum as a function of energy and angle is shown in Figures 4 and 5. These results are subsequently used to calculate the expected albedo proton spectrum observed by the CRaTER instrument by folding in the D6/D4 and D6/D2 angular response function for each orientation calculated in the next section. The number associated with 'D' refers to a detector number in CRaTER.

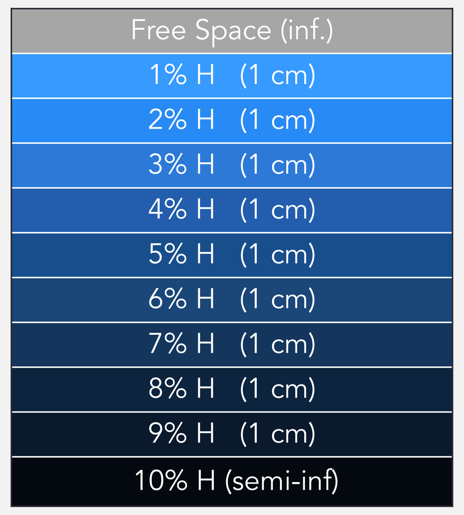

Figure 1. A representation of the wet regolith layers.

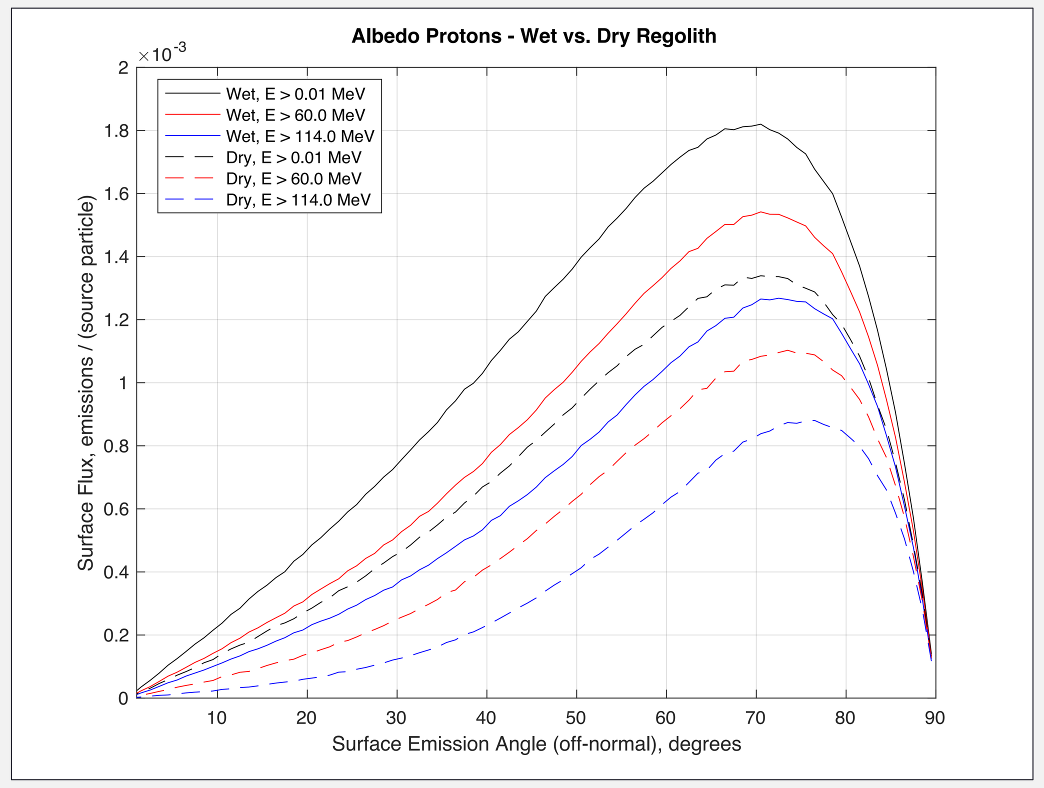

Figure 2. The lunar albedo proton surface emission spectrum binned as a function of emitted angle. The red and blue colors represent the D6/D4 and D6/D2 coincidence energies, respectively. Solid and dotted lines indicate wet and dry regolith.

CRaTER Response Model

The angular surface emission spectrum for particles observed via D6/D4 and D6/D2 coincidence (see Figure 3) in the CRaTER instrument changes with spacecraft orientation. The angular responses for both the limb-pointing and nadir-pointing orientations were calculated independently using the MCNP6 Monte Carlo radiation transport code. The angular response functions are folded into the albedo proton emission distribution (Figures 4 & 5) to obtain the expected albedo proton spectrum observed by the CRaTER instrument. Figures 6 and 7 illustrate the expected spectra of albedo protons for the limb and nadir orientations for all permutations of altitude (50 km, 180 km), coincidence (D6/D4, D6/D2), and regolith composition (dry, wet). The vertical black line indicates the threshold energy required to trigger the appropriate coincidence. The mean energy of detectable protons for each orientation is marked with a colored vertical dotted line and dot.

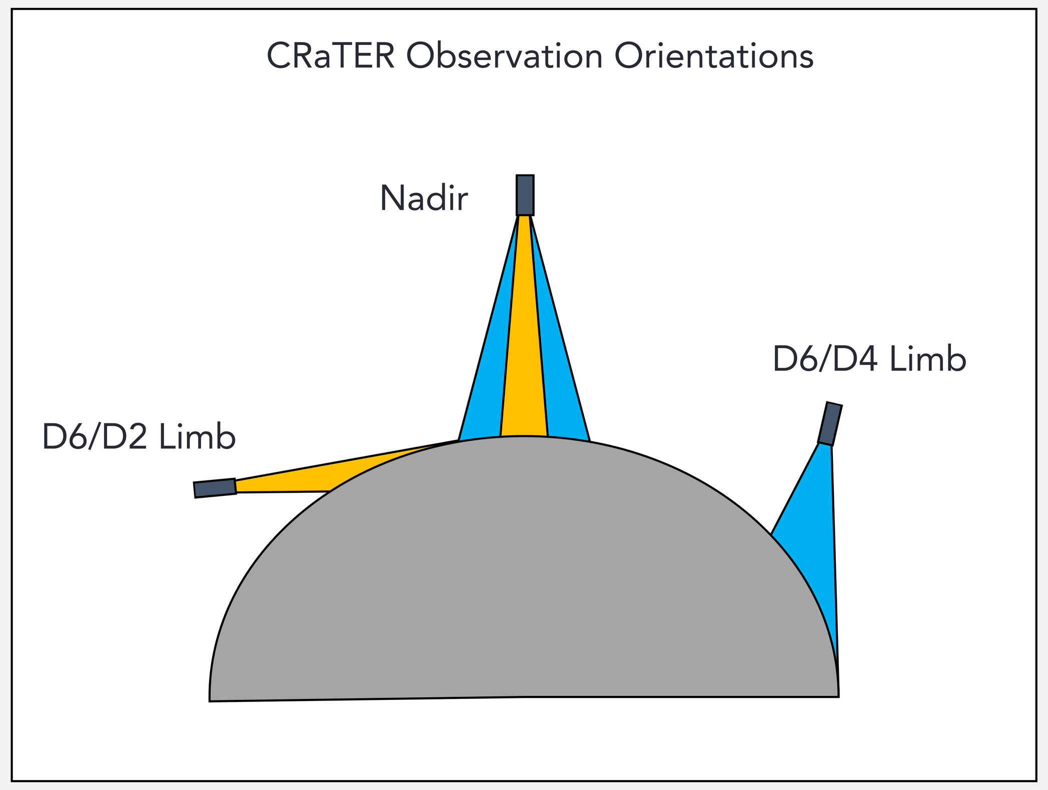

Figure 3. A simplified 2-dimensional representation of the CRaTER observation orientations.

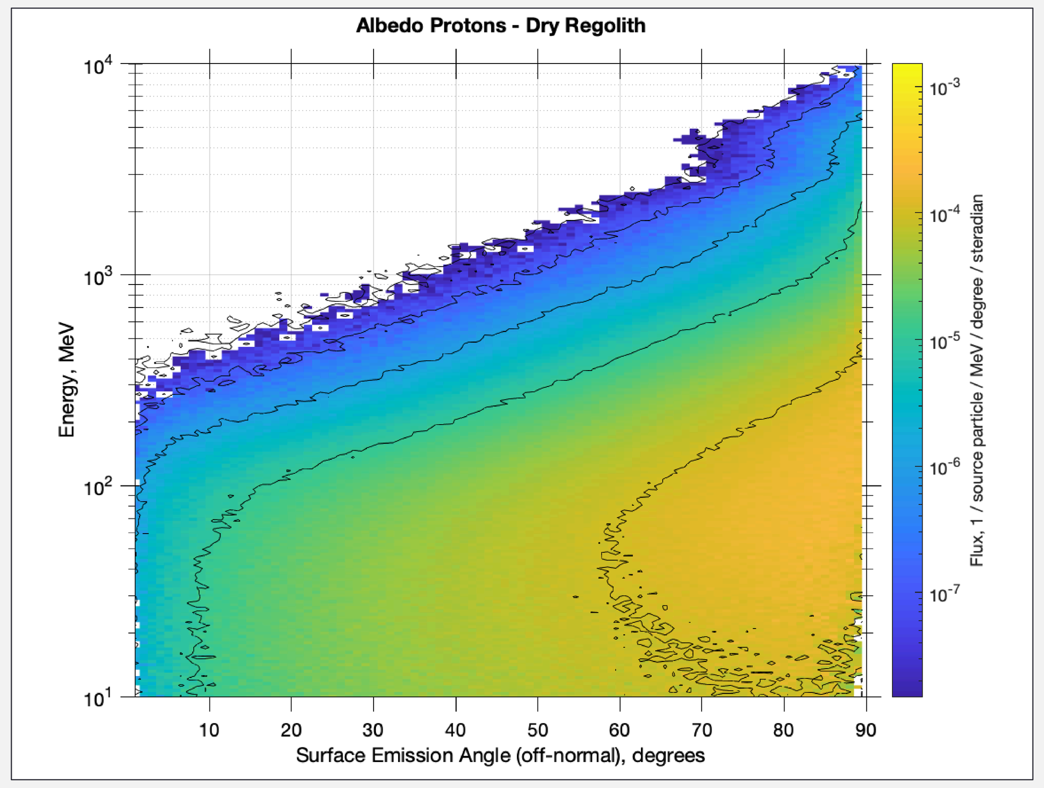

Figure 4. The lunar albedo proton surface emission spectrum binned as a function of both energy and emitted angle for dry regolith.

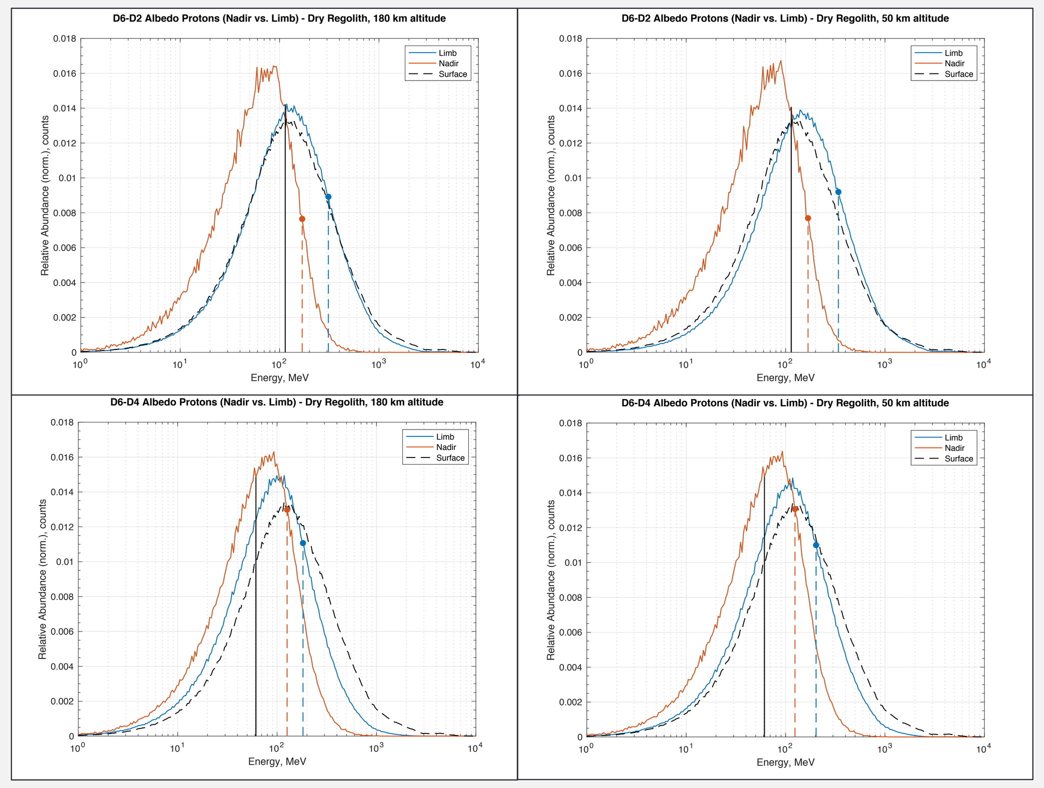

Figure 6. Lunar albedo proton spectra binned as a function of energy for all permutations of altitude, coincidence requirement, and spacecraft orientation for dry regolith.

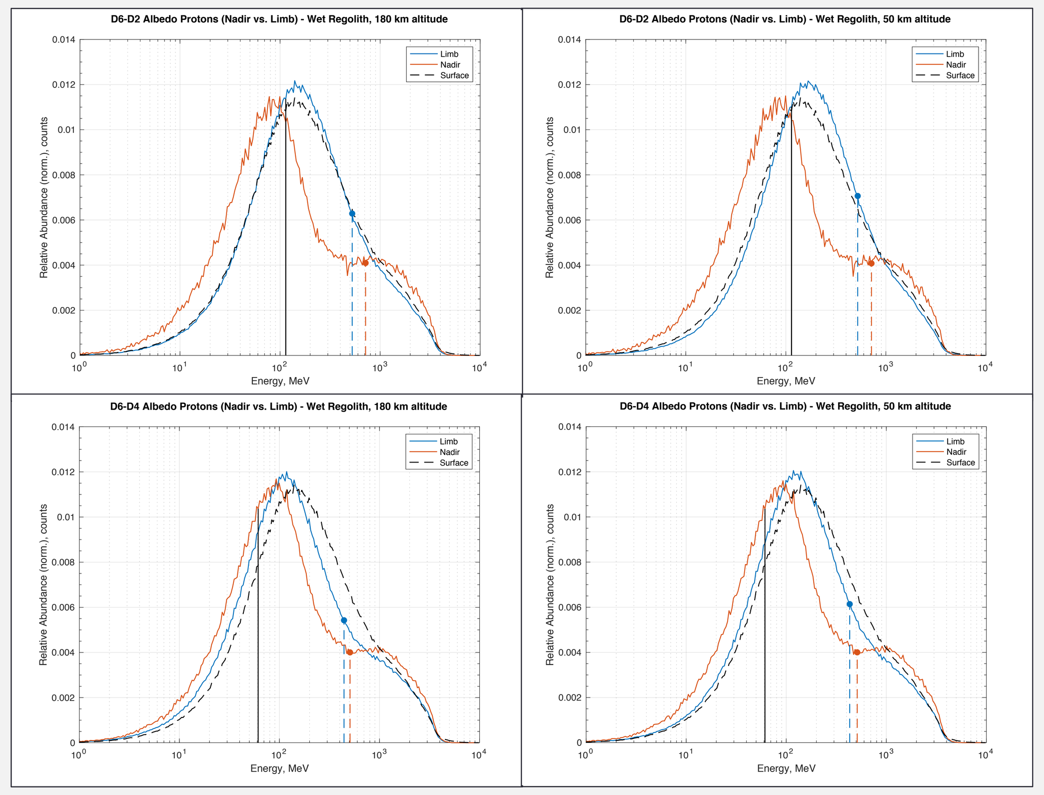

Figure 7. Lunar albedo proton spectra binned as a function of energy for all permutations of altitude, coincidence requirement, and spacecraft orientation for wet regolith.

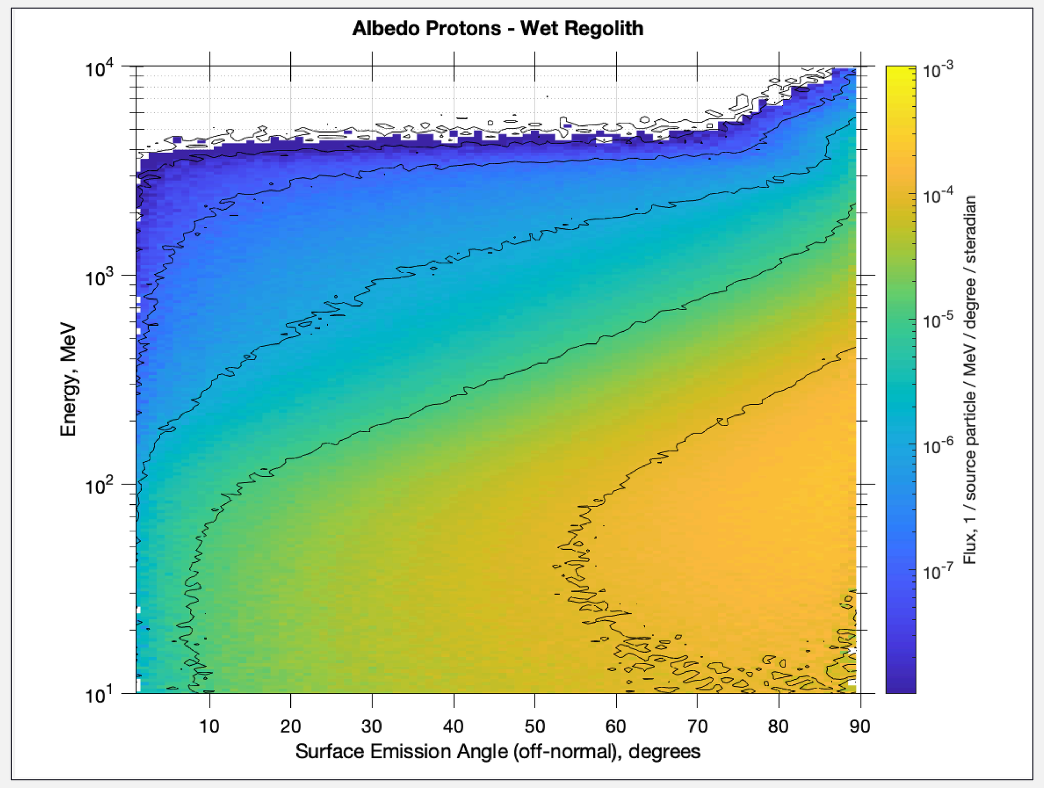

Figure 5. The lunar albedo proton surface emission spectrum binned as a function of both energy and emitted angle for wet regolith.

Results

A comparison of Figures 4 & 5 shows that, while there is little difference in the surface emission spectra for large angles off-normal, there is a significant enhancement expected in smaller angles at high energies in the case of hydrogenated regolith. A comparison of Figures 6 & 7 shows that both the limb and nadir spectra observed by CRaTER are affected by the high-energy enhancement when viewing hydrogenated regolith. Of the two observation modes, the nadir viewing spectra are most strongly affected, especially for the D6/D2 coincidence.

Conclusions

- We have developed methodology for calculating expected albedo proton spectrum measured by CRaTER via D6/D4 & D6/D2 coincidence for both hydrogenated and dry regolith.
- In hydrogenated regolith, the mean proton energy is higher when observed in nadir orientation versus the limb orientation for all coincidences and altitudes.
- In dry regolith, the mean proton energy is higher when observed in limb orientation versus the nadir orientation for all coincidences and altitudes.

Acknowledgements

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References

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[4] O'Neill, P. M. et al., NASA/TP–2015–218569. (2015)