Signatures of volatiles in the lunar proton albedo


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ABSTRACT

We find evidence for hydrated material in the lunar regolith using “albedo protons” measured with the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter (LRO). Fluxes of these albedo protons, which are emitted from the regolith due to steady bombardment by high energy radiation (Galactic Cosmic Rays), are observed to peak near the poles, and are inconsistent with the latitude trends of heavy element enrichment (e.g., enhanced Fe abundance). The latitudinal distribution of albedo protons anti-correlates with that of epithermal or high energy neutrons. The high latitude enhancement may be due to the conversion of upward directed secondary neutrons from the lunar regolith into tertiary protons due to neutron–proton collisions in hydrated regolith that is more prevalent near the poles. The CRaTER instrument may thus provide important measurements of volatile distributions within regolith at the Moon and potentially, with similar sensors and observations, at other bodies within the Solar System.

1. Introduction

Water on the Moon has been studied intensively for more than a century (e.g., Lucey, 2009; Pieters et al., 2009). Early results from sample return missions of the 1960’s suggested that the Moon was dry. Samples from the Apollo missions did not show the water-bearing minerals common on Earth (Papke et al., 1991). Even the trace water or hydrous minerals found in Apollo samples were thought to be the result of contamination (Taylor et al., 1973, 1974). More recent studies (Saal et al., 2008) indicate the presence of water in the Moon’s interior, as inferred from Apollo 15 green and Apollo 17 orange volcanic glasses. These are thought to represent the most primitive materials from the mantle within the collection of lunar samples. The result is motivating a broad range of new research into samples collected throughout the Apollo era.

Volatile accumulation in permanently shaded regions (PSRs) at the poles of the Moon has been suggested for many years, dating back to before the Apollo era (Urey and Korff, 1952; Watson et al., 1961) and beyond (e.g., Arnold, 1979). The Lunar Prospector Neutron Spectrometer (LP-NS) utilized neutron spectroscopy to probe the lunar regolith down to depths of ~50 cm, specifically showing the high abundance of hydrogen (H) or hydrogenous species at very high latitudes, where epithermal neutron emission is suppressed (Feldman et al., 1998, 2001; Lawrence et al., 2006; Eke et al., 2009). While these regions show suppressed neutron emissions, the specific association with PSRs has not been fully established and remains an important objective. The Lunar Exploration Neutron Detector (LEND) on the Lunar Reconnaissance Orbiter (LRO) subsequently provided global maps of lunar neutron fluxes (Litvak et al., 2012), though the detection is complex and
subject to potential backgrounds that could degrade the resolution (Lawrence et al., 2011a; Miller, 2012; Miller et al., 2012; Teodoro et al., 2014).

Infrared spectroscopic measurements have offered new information about the lunar surface – unambiguous identification of OH and H$_2$O (Clark, 2009; Pieters et al., 2009; Sunshine et al., 2009). For example, Pieters et al. (2009) utilized the Moon Mineralogy Mapper ($M^3$) on Chandrayaan-1 to detect absorption features in the wavelength range from 2.8 to 3.0 $\mu$m on the lunar surface. These features indicated the presence of materials containing OH and H$_2$O. Interestingly, the absorption feature is widely distributed, and strongest at high latitudes and at several fresh feldspathic craters.

There is some contrast between these absorption measurements and the neutron spectrometer data. Whereas the latter indicate pronounced deficits of albedo neutrons in regions around polar PSRs, the absorption features observed by $M^3$ are far more widespread at high latitudes, extending well below 80° latitude. A key difference in these observations is that the $M^3$ absorption features originate from H in the upper surface (as thin as tens of microns). In contrast, the neutron data is generally sensitive to H to larger depths in the regolith (up to ~50 cm) (Lawrence et al., 2006, 2011b). Fast neutron measurements (e.g., from LP-GRS) are, in principle, capable of identifying near-surface deposits. Combining the neutron and IR measurements suggests that there is a widespread thin upper layer (a veneer of ~mm–cm) containing OH and H$_2$O at the Moon, whereas, at very high latitudes (above ~80°), the deeper regolith is rich in H. Water molecules residing in polar cold traps can be redistributed by ion sputtering or impact vaporization (Farrell et al., 2013). These polar-ejected molecules would contribute to the water and OH veneer observed in $\sim$3 $\mu$m absorption features.

In this paper, we discuss a new technique for observing hydrated material at the Moon using the energetic proton albedo (Wilson et al., 2012, this volume; Looper et al., 2013). Until recently, it has been unclear how the energetic proton albedo could be used to infer compositional signatures of the regolith. This paper assembles laboratory measurements and 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. Quantitative calculations and simulations are used to explore potential implications of these results.

2. The Cosmic Ray Telescope for the Effects of Radiation (CRaTER)

The method to identify the energetic particle albedo in CRaTER measurements is thoroughly detailed by Wilson et al. (2012), Looper et al. (2013), and Spence et al. (2013). The CRaTER instrument (Fig. 1) consists of a stack of six Si detectors with three pairs of thin (~150 $\mu$m) and thick (~1 mm) detectors separated by two blocks of tissue-equivalent plastic, or TEP (see Spence et al., 2010; Case et al., 2013). In the nominal spacecraft attitude, the sensor is oriented with its axis pointing vertically relative to the lunar surface. The two zenith-facing detectors (D1, thin, and D2, thick) are the first to be penetrated by galactic cosmic ray (GCR) and solar energetic particle (SEP) radiation incident from above (zenith), whereas the bottom detectors (D5, thin, and D6, thick) are the first to be penetrated by upward-going (nadir) radiation from the Moon – the energetic particle albedo. The middle detectors (D3, thin, and D4, thick) are separated from the D1/D2 detectors by 54 mm of TEP and from the D5/D6 detectors by 27 mm of TEP. Low- and medium-energy particles leave distinctive signals in CRaTER that allow us to distinguish their direction (zenith versus nadir) and therefore their source (the Moon versus deep space). Any energy deposit in any detector triggers an event. All energy deposits from all detectors are recorded. Data products are in terms of LET, the amount of energy deposited per path-length ($\Delta E/\Delta x$) as a particle transits through each detector.

GCR protons, GCR alphas, GCR heavy ions, and albedo protons can be identified in cross-correlation plots of energy deposits in D6 and D4, as shown in Fig. 2 here and Fig. 2 of Looper et al. (2013). Every particle that passes through both D4 and D6 deposits a specific amount of LET in each detector, and this pair of LETs can be plotted on a 2-D histogram (Fig. 2). Albedo protons coming from the nadir direction are only capable of depositing LET pairs in a small region of the histogram, which is referred to as the albedo proton “swoosh” (Wilson et al., 2012). We make a count of every detection event that falls in that (D4, D6) range that corresponds to albedo protons. However, other secondary effects can create events that look like albedo protons from the Moon, even though they are not. For instance, a high-energy alpha particle that hits the instrument from the side and passes through only D4 (and deposits a low amount of LET consistent with a proton) will normally not be a problem because no energy registers in D6. However, if that same side-penetrating alpha particle also produces a secondary proton in the TEP that then travels to D6, the event...
might end up depositing LET in D4 and D6 in the same region where real albedo protons register. For this reason, it is necessary to differentiate between the albedo protons and background.

Approximately 60% of the events in the albedo proton “swoosh” are actual albedo protons, leaving 40% which are effectively background noise. We know the level of background noise because it varies smoothly with LET, and we can measure it on either side of the albedo proton swoosh. Using this method, we can select out the albedo proton track and subsequently map the albedo protons at the Moon (Wilson et al., 2012, this volume).

3. Laboratory measurements

To enhance our understanding of CRaTER measurements, we continue to use the CRaTER Engineering Model (CRaTER-EM) in a variety of laboratory measurements, as detailed below. The CRaTER-EM is deliberately designed through advanced prototyping to provide a functionally identical unit on the ground that could help us assess the in-flight performance of the flight model. The CRaTER-EM telescope is mechanically and materially identical to the flight model, most importantly including the mechanical design, configuration, and structure, the front-end analog and digital electronics, the TEP material and thicknesses, and the solid state detectors; both the TEP and the detectors were from the same lots used for the flight model. The only differences between the CRaTER-EM and flight model are in the final coatings and a few in-consequential electronic components in the digital processing unit, far from the telescope section. Prior to launch, the two instruments were validated as being functionally identical in how they respond to ionizing radiation.

With a particle accelerator beam directed at a specific target and the CRaTER-EM instrument aligned with D5/D6 facing the target, the correlation between D6 and D4 energy deposits is used to identify the proton albedo. Three beam runs, in particular, have been helpful.

From 2012 to 2014, the CRaTER team traveled several times to two particle accelerator facilities (the Heavy Ion Medical Accelerator in Chiba Japan, HIMAC; and the Massachusetts General Hospital Proton Beam Facility, MGH) to perform laboratory studies with CRaTER-EM. Fig. 3 depicts one of the experiments performed in these studies, in which the beam is directed at a target composed of JSC-1A regolith simulant (McKay et al., 1993). JSC-1A (a reproduction of JSC-1) is a glass-rich basaltic ash that approximates the bulk chemical composition and mineralogy of some lunar soils (Miller et al., 2009). It has an average particle size <1 mm (see also, http://isru.msfc.nasa.gov/lib/workshops/2009/03_JSC-1A_Lunar_RegSimulant_Update_BGustafson.pdf).

The first series of our beam runs was performed May 29 through June 1, 2012 at the Heavy Ion Medical Accelerator (HIMAC). In addition to running several of our first albedo tests, we also made measurements to determine the effects of scattering within the instrument (Zeitlin et al., 2013). The angular response to albedo protons is key to understanding a number of effects including altitude distribution of albedo protons at the Moon, the observational field-of-view on the Moon at a given time, and the potential for backgrounds caused by energetic particles that penetrate from the side.

The angular response is also critical for determining whether the proton albedo observed by CRaTER is contaminated by primary GCRs or by particles arriving from the lunar limb (at large angles with respect to the zenith/nadir line). Fig. 4 shows some of the results from the test using the 160 MeV $^4$He beam. The beam in this case was directed into the bottom of the instrument with the D5/D6 detectors facing into the beam. Incidence angle is measured with respect to the boresight, down the center-axis of the 6 detectors. The pivot point was chosen at the position of D5/D6. We show the D4–D6 detector coincidence count rate (blue).

The angular response is roughly consistent with a simple geometric model of the instrument, indicating an acceptance cone up to angles of ±30° with respect to normal incidence. For acceptance angles outside ±30°, we observe effects associated with secondary particles, primarily electrons (delta rays) within the

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1 For interpretation of color in Fig. 4, the reader is referred to the web version of this article.
instrument, which leads to a slight sensitivity to particles with large incidence angles. Nonetheless, the response function is quite small (<1%) at these large angles. The orientation of the spacecraft and CRAfTER is known to within a fraction of a degree with one-second time resolution. The field of view of CRAfTER (60° full width) dwarfs the pointing precision. During the periods analyzed in this paper (and over the majority of the LRO mission to-date), LRO/CRAfTER is always close enough to the Moon (200 km or closer) to ensure that, when pointed at nadir, the Moon completely fills the D4 + D6 field of view by a wide margin. The Moon thus shields 100% of cosmic rays that would otherwise come from the nadir direction.

A fundamental result derived from these angular response measurements is that CRAfTER is insensitive to primary particles at incidence angles larger than ~40°. This demonstrates (1) that the acceptance cones of correlated measurements from zenith (D2–D4 detector coincidence) are distinct from those of correlated measurements from nadir (D6–D4) and (2) that side-penetration of GCRs contributes very little compared to particles directed from nadir in D6–D4 correlated measurements. Therefore, the instrument is capable of separating deep space radiation sources (GCRs and SEPs) from albedo (upward directed particles originating from the Moon). Further, because the angular response is roughly consistent with a simple geometric model (acceptance cone up to angles of ~±30°), the instrument is only weakly sensitive to side penetrators or proton albedo from the horizon. Finally, these measurements are of particle events that trigger both D4 and D6 detectors, without reference to the actual energy deposits in those detectors; correlating energy deposits to pick out the albedo proton track as in our previous work suppresses backgrounds even further.

During a second beam run (May 28–30, 2013), we tested how materials of various compositions emit albedo protons. During these laboratory experiments, we reproduced the analysis of albedo proton from flight data. In other words, we applied selection criteria in the D4–D6 coincidence curves as a function of linear-energy-transfer (LET) to distinguish albedo protons (~65–120 MeV) from other species. In Fig. 5, we have taken the ratio of the albedo proton rate from a given target material (wet regolith simulant, water, and polyethylene, as listed on the horizontal axis) versus that from dry regolith simulant. Blue bars show results when the target was exposed to a 160 MeV H beam, and red bars show results when the target was exposed to a 800 MeV/nuc Si beam.

The details of target materials are listed here:

- Dry regolith simulant of total mass 25 kg was placed in a bucket placed upright for beam tests. The bucket had a 26 cm bottom diameter, 30 cm top diameter, and 38 cm height.
- Wet regolith simulant was placed in an identical bucket with total mass (regolith plus water) of 27.4 kg: 2.4 kg water, (8.8% water by mass), plus 25 kg of regolith simulant. The water was well mixed with regolith and the uniformity of mixing was checked by making albedo observations with different orientations of the bucket. The 8.8% mass fraction of water used in these tests is quite a bit larger (by ~3×) than the mass fractions determined from neutron spectroscopy. However, these initial tests were conducted to establish what, if any, effect would be observed in the proton albedo with the presence of water within regolith simulant. It was hoped that a large mass fraction of water would result in a change in the observed yield larger than statistical fluctuations.
- The water target was contained in a 9 L bucket with 22 cm bottom diameter, 27 cm top diameter, and 18 cm height.
- The polyethylene target had a face 20 cm × 20 cm and a 6 cm depth down the beam axis.

In each case, the CRAfTER-EM was placed 111 cm from the target, with the D5/D6 side of the detector facing the target (see Fig. 5).

The key result from Fig. 5 is that hydrogen enrichment suppresses the albedo proton yield. The albedo protons are created by nuclear collisions in which a target nucleus becomes highly excited, and returns to its ground state by isotropic emission of nucleons (protons, neutrons and other particles). This process is referred to as nuclear evaporation, i.e., the emission of secondary particles from the breakup of excited nuclei. However, the nuclear evaporation process does not occur with a hydrogen nucleus, as
there is no excited residual nucleus after a collision, and therefore no de-excitation. Hydrogen is also very effective at causing incident particles to lose energy. Therefore, in hydrogenous materials, more of the incident energy goes into ionization and forward-going nuclear interaction products than in non-hydrogenous materials. Both enhanced forward-going nuclear interaction products and reduced nuclear evaporation from materials rich in H suppresses the yield at small angles off the target surface normal where the CRaTER-EM is placed to measure albedo particles.

A third test of the hypothesis that H-rich targets have reduced nuclear evaporation and enhanced forward-going secondary products for H-rich was conducted at the Massachusetts General Hospital Proton Beam Facility (MGH) in 2013 (November 9–10). We irradiated an Al target (as a surrogate for regolith) and a water target with a 230 MeV H beam. Note that the Al target instead of regolith simulant was used to reduce material costs of the beam run. Previously used regolith simulant remained too hot for transport after the HIMAC beam runs. Results from simulations have shown that the average molecular mass of irradiated material is the dominant factor in determining the proton albedo. Therefore, Al was considered a suitable proxy for regolith due to the similarity of the atomic mass of Al compared to the average atomic mass of regolith simulant. Clearly, future tests with regolith simulant are desired to refine our understanding of the proton albedo.

For the MGH tests, the CRaTER-EM was placed again at 110 cm from the target, and moved in a circle with this radius around the calculated stopping point of the beam in each target. The Al target was a cylinder with the axis parallel to the beam. The cylinder length was 18.42 cm and diameter was 12.7 cm. For the water target, a small rectangular glass tank was used. The tank had a length of 36 cm along the beam line, a width of 18 cm, and a height of 13 cm. The beam was centered on the 18 × 13 cm face.

We found that, with respect to the Al, the water suppressed albedo protons at low angles with respect to the target surface normal and enhanced albedo protons at large angles (see Fig. 6). These results support the idea that enhanced forward directed secondaries from H collisions and reduced nuclear evaporation suppresses the proton albedo at low angles with respect to the surface normal (Fig. 7). At large angles with respect to the surface normal, forward scattering causes an excess of secondaries that can escape the target through its sides, i.e., an excess of albedo protons due to forward scattering.

Geant4 simulations (not shown) were conducted to provide insights into the angular dependence of the proton albedo measured during the MGH experiment (Fig. 6). It is clear that many of the extra protons seen from the water target at large angles are punching through the sides of the target.

4. Observations

Laboratory measurements suggest that the presence of H 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. 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.

The nuclear evaporation process operating at the maria, which are rich with heavy atoms such as Fe, should result in a larger proton albedo than at the lunar highlands (see Fig. 8). The CRaTER observations consistently show enhancement in the proton albedo in the maria (Wilson et al., this volume).

The anticipated 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 have formed latitudinal profiles of albedo proton data observed by CRaTER (Fig. 9) from the most recent albedo proton maps (Wilson et al., this volume), which were corrected for altitude and background effects. The yield shown in Fig. 9 is calculated as the ratio of albedo protons in the D4–D6 coincidences relative to the GCR protons measured by CRaTER in coincidences across all three thick detectors (see Wilson et al., this volume, for details). The latitudinal trend from the highlands regolith generally shows an enhancement in albedo.
protons at high latitudes, as opposed to the suppression expected from hydrogen-rich regions. We distinguish the lunar highlands and maria using the iron abundances derived from the Lunar Prospector Gamma Ray Spectrometer (Lawrence et al., 2002). All pixels with an LP iron value above 10 (in arbitrary units) are counted as maria, and all pixels less than or equal to 10 are counted as highlands.

The highest latitude bins in both the N and S of Fig. 9 (top panel) show some flattening, but it is not at all clear if this is statistically significant. It is possible that this flattening is due to enhancements in hydrogen at very high latitudes (e.g., within PSRs). Clearly, better statistics are needed to resolve the detailed trends of the proton albedo at the highest latitudes. The overall trend of increasing albedo proton yield with latitude remains to be explained.

An important question is whether the latitude trend may reflect some residual uncorrected altitude dependence. To test for this possibility, we have formed latitudinal albedo proton profiles during the first two and a half years of the mission (9/2009–1/2012) when LRO was in a quasi-circular orbit. Fig. 10 shows the latitude dependence of the “relative” yield with respect to the yield near the equator. The first albedo proton map (Wilson et al., 2012) was formed with different techniques for background subtraction. By plotting the relative yield, we can directly compare previous results from the first proton albedo map with more recent results. While the data have much larger uncertainties, there does appear to be a trend similar to that seen in Fig. 9, in which higher latitudes show a slightly increased yield in comparison to lower latitude regions. Therefore, data from the period when LRO was in a quasi-circular orbit suggests that the latitude trend is real and is not an artifact of an uncorrected altitude dependence in the proton albedo measurements.

As previously discussed, the orientation of the spacecraft and CRaTER are known to within a fraction of a degree with one-second time resolution. During the periods analyzed here, LRO/CRaTER is always close enough to the Moon (200 km or closer) to ensure that, when pointed at nadir, the Moon completely fills the D4 + D6 field of view by a wide margin. The Moon thus shields 100% of cosmic rays that could come from the nadir direction. Further, as discussed in the last paragraph, we correct the data for (as yet incompletely analyzed) altitude effects and the data when LRO was in a circular orbit also shows a latitude dependence in the proton albedo that peaks near the poles. Any long-term effect (from changing GCR energy spectrum, for instance) will be smeared out over latitude, as the time scale for changes is much longer than the 1-h traverse of LRO from pole to pole. To our knowledge, we have either ruled out or corrected for every orbital or secular effect that could cause a latitude dependence in the proton albedo.

We have also studied the statistical significance of the latitude trend. We improve statistics by mirroring data across the equator. Fig. 11 shows the latitude trend in the mirrored data. We have minimized the χ² to find the best fit to a line. The three lines and the shaded region show the χ² minimum (solid line) and the uncertainty (dashed lines). The derived slope is 1.01% ± 0.34% from pole to equator.

The χ² minimization is shown in Fig. 12. The uncertainties used in the analysis include both statistical uncertainties and systematic uncertainties due to background subtraction. As a result, the fit has a reduced χ² that is less than 1 (red curve). When only statistical uncertainties are included, the reduced χ² minimum approaches 1, as expected. The curvature in the χ² dependence as a function of the slope is used to derive the fit uncertainty (the technique for deriving fit uncertainty from the χ² is outlined in the appendix of Schwadron et al., 2013).

Several additional fitting methods (Livadiotis, 2007) have been used to test the statistical significance of derived trends. The parabolic model has been tested for both the regular and mirrored data and it was found to be statistically the most significant...
\[ Y_p = A + B\lambda + C\lambda^2 \]  

where \( Y_p \) is the albedo proton yield, \( \lambda \) is the latitude expressed in degrees, and the constants are \( A = 0.080109 \pm 0.000114 \), \( B = (-0.84 \pm 1.28) \times 10^{-5} \), and \( C = (9.73 \pm 3.14) \times 10^{-8} \). The function has a local minimum close to zero latitude, \( \sim 4.3^\circ \). Results of the statistical analysis suggest that the proton albedo yield not only increases with latitude but increases more rapidly at higher latitudes than at low latitudes. The slope is characterized by an increasing rate of \( d^2Y_p/d\lambda^2 \approx 2C \sim 2.0 \pm 0.6 \times 10^{-2} \) deg\(^{-2}\). From pole to equator, this fit yields a change of \( 0.89\% \pm 0.46\% \) in the N and a pole-to-equator change of \( 1.08\% \pm 0.46\% \) in the S. Therefore, application of statistical methods reveal not only the presence of a significant latitudinal trend, but also the predominance of polar regions in increasing the albedo proton yield.

The latitude trend in the proton albedo is very difficult to explain. Despite an extensive search for features of bulk elemental
abundance patterns that can explain the trend, we found none that predict a trend in the direction that is observed (Fig. 9). For example, Fig. 13 shows the latitudinal profile of Fe abundance, Ti abundance and hydrogen from the highlands (lower panel) and with fast and epithermal secondary (albedo) neutrons (upper panel). Because Fe and Ti abundances peak at low latitudes, nuclear evaporation should enhance the proton albedo from low latitudes. Similarly, since hydrogen-abundance peaks at the poles, it should suppress the proton albedo from the poles. The secondary neutrons are suppressed in the high latitude highland regolith, as is consistent with enhancements in hydrogen.

One possibility is that there is a deep (≈50 cm) enhancement of heavy elements in the polar highlands in both hemispheres that was missed by the gamma ray measurements because they are not sensitive to the composition of the regolith down to the depths (≈50 cm to 1 m) most relevant to albedo proton production. While we cannot entirely rule this out as the source of the albedo proton trend observed by CRaTER in the highlands, there is currently no other data that suggests such high-latitude concentrations.

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, attempts at rebinning the albedo proton data fail to reveal any significant, systematic trend of suppression at high latitudes. The only small indication of suppression comes from the two most poleward bins in the N and S that indicate a small reduction in proton albedo compared to neighboring data points (see the top panel of Fig. 9). However, even this trend is potentially a fluctuation due to low counting statistics.

5. Discussion

Initial laboratory measurements have been used to identify two key physical mechanisms that modulate the proton albedo. Nuclear evaporation should cause an increased proton albedo from regions with higher concentrations of heavy atoms. In contrast, the forward-directed secondaries from collisions of primary incident particles on hydrogen within regolith tends to suppress albedo. The resulting observational signatures are, as follows:

- Regolith rich with heavy elements such as Fe should generate a larger surface flux of albedo protons than regolith with smaller heavy element abundances. This signature may be observed in the higher albedo proton yield from the maria in comparison to the highlands (Wilson et al., this volume).
- Regolith rich with hydrogen should lead to a suppression of the albedo proton yield. This suggests that the higher abundance of hydrogen at high latitudes should suppress albedo proton yield. In fact, CRaTER measurements indicate precisely the opposite trend. The poles generally show enhanced albedo proton yield.

We consider an additional physical mechanism in addition to nuclear evaporation that may help account for the observed enhancement of albedo protons at high latitudes, as detailed in the following subsections.

5.1. Tertiary protons

One possible explanation of the proton albedo enhancement at high latitudes is illustrated in Fig. 14. The nuclear evaporation process from deep in the regolith produces abundant secondary particles in all directions. The re-emitted secondary radiation from the lunar surface, the albedo, is composed of a wide range of different particle types including protons, neutrons, and other species.

The highest flux of these albedo particles from the surface is in the form of neutrons up to ~100 MeV (Looper et al., 2013). If an upward-traveling 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.

Consider the presence of a hydrated layer near the lunar surface. To roughly quantify the process, we take the nominal proton albedo flux $F_p$ and neutron albedo flux $F_n$ near 60 MeV. In the presence of the hydrated layer, we expect an enhancement in the proton flux given by $F_p' = F_p + F_p(dn_{H} / \sigma_{np})$ where $dn_{H}$ is the column density of hydrogen in the upper hydrated layer and $\sigma_{np} \approx 1.25 \times 10^{-25}$ cm$^2$ is the neutron–proton cross-section at 60 MeV (Norbury, 2008). Since the quantity $dn_{H} / \sigma_{np}$ is small, we can approximate the fractional excess in the proton yield as $\Delta \approx (dn_{H} / \sigma_{np})F_p / F_p$. Inverting the equation, we solve for the column density of hydrogen needed to provide the observed excess in the yield, $dn_{H} \approx \Delta F_p / (F_p \sigma_{np})$. Using the observed proton albedo enhancement of $\Delta = 1.01 \pm 0.34\%$ at high latitude, and the ratio $F_n / F_p \approx 20$ from simulations (Looper et al., 2013), we arrive at a needed column density of $dn_{H} \sim 4.0 \pm 1.4 \times 10^{21}$ cm$^{-2}$.

To gain a better conceptual understanding, consider a scenario in which the top hydrated layer has a depth of $d \sim 20$ cm, giving a mass density of $H$ of $\rho_H \sim 3 \times 10^{-4}$ g cm$^{-3}$ or ~200 parts per million (ppm) in excess mass assuming a regolith mass density of 1.5 g cm$^{-3}$. Such an excess is comparable to the modeled hydrogen abundances in cold traps of 200–4000 ppm (Table 1, Teodoro et al., 2010).

An important question is how deep the hydrated layer could be to still result in an excess of albedo protons. The results of laboratory measurements suggest that the hydrated material should be less than ~1 m in depth to result in an excess. However, there are some significant limitations of the laboratory (beam) measurements that prevent a definitive answer at this time. First, the laboratory measurements did not consider the large spectrum of energies and heavy nuclei in the GCR spectrum. In particular,
higher energy GCR (>1–10 GeV) nuclei have large ranges in regolith extending down to many meters. Second, the laboratory measurements utilized targets with relatively thin targets (~1 m) and therefore excluded interactions from the deep regolith. Both of these factors motivate studies involving detailed simulations to understand the response of the hydrated regolith.

5.2. Geant4 simulations of hydrated regolith

The laboratory tests, while excellent indicators of the physical processes in play, do not completely replicate the behavior when the target material is regolith at the Moon with a detector located tens of kilometers above the surface. GCR particles are essentially isotropic in deep space and therefore are incident at the lunar surface with velocities uniformly distributed in the downward hemisphere. Further, GCRs arrive with a wide spectrum of energies and are composed of a mix of many particle species. Therefore, to capture these complexities, we simulate how GCRs interact with the regolith using Geant4 simulations.

The Geant4 simulations used in the analysis of Looper et al. (2013) were recently extended to study the dependence of the lunar proton albedo on regolith composition. The simulations assume the lunar regolith is illuminated uniformly from above by GCRs (since GCRs are essentially isotropic in free space). The simulation adopts an input GCR spectrum based on the Badhwar–O’Neill model (O’Neill, 2010), which provides GCR fluxes for all elements up to nickel (with extrapolation for heavier elements, not used here). GCR fluxes in the Badhwar–O’Neill model are parameterized by a single constant, the modulation parameter $\Phi$, which has dimensions of rigidity (relativistic momentum per unit charge). The simulations were performed for $\Phi = 417$ MV, as appropriate for the recent deep solar minimum as observed by CRaTER early in its mission. The regolith was modeled as a slab of ferroan anorthosite (composition given by Gaunaut et al., 2000). The simulation was run with a 10 m slab, and a density of 3 g/cm$^3$. The modeled mass density is larger than that of typical regolith (~1.5 g/cm$^3$); however, the nuclear interactions and particle escape depend only on the column mass density (g/cm$^2$), so that mass density does not affect the results. The simulation also used surface dimensions of 1 square km in the plane of the horizon. Additional details concerning the simulation are discussed by Looper et al. (2013), and results are shown in Fig. 15. The earlier simulations included lunar albedo only from GCR protons and alpha particles; the results shown in this figure include GCR primary species up to Ni.

Two significant features are apparent. CRaTER viewing of albedo protons is restricted to small angles off the surface normal (<30°). Over this angular range in Fig. 15, we observe the highest flux of secondary particles for energies between several MeV and ~100 MeV. The secondary particle flux increases at larger angles off the surface normal and the secondary fluxes extend to higher energies at these angles. This is a testable prediction for future observations made off-nadir.

We also simulated the albedo from wet as well as dry regolith. These initial simulations were conducted with only GCR protons to simplify analysis and reduce run-times. In our first simulations of wet regolith, we added 50% water by mass throughout the regolith. This large water fraction was necessary in order to bring out the differences in simulation results with reasonable statistics; the magnitude of the differences should scale approximately linearly with lower water fractions. The difference between the wet and dry regolith is shown in Fig. 16 (only GCR proton primaries were modeled for this simulation, but they dominate the production of albedo particles). Note that for shallow angles off the surface normal (<30° for the CRaTER field of view), we observe a clear deficit in albedo protons. Above 60°, this deficit transitions into an enhancement as a result of the enhancement of forward-directed secondaries from interactions in hydrogen enriched material, as detailed in the previous section. The results of the Geant4 modeling support our interpretation of laboratory measurements.

In a second set of simulations involving wet regolith, we studied the proton albedo from regolith with 10% by mass of hydrated material that extends down to varying depths. These simulations were run explicitly to search for possible enhancements in the albedo due to the presence of tertiary protons emanating from shallow layers near the top of the regolith. GCR protons are used as input to the regolith, and heavier species are neglected to reduce run times and simplify analysis. Fig. 17 shows the results of these simulations for the fraction of the proton albedo from wet vs. dry regolith. We observe a significant excess in albedo protons from wet regolith appears for a depth of hydrated material of ~10 cm. However, we observe a deficit of the albedo protons from wet regolith for cases where the depth of the hydrated layer exceeds ~20 cm.

These simulations support the interpretation of the observed trend in latitude for albedo protons as the result of larger amounts of hydrated material within regolith at high latitudes. However, further work using both simulations and laboratory studies is needed to clarify the amount of water in the hydrated layer needed to explain the trends observed by CRaTER. In the simulations

**Fig. 15.** Geant4 simulations of protons from the regolith due to GCR bombardment. Protons are shown as a function of energy (vertical axis) and angle off the surface normal (horizontal axis). Note that an excess of protons are seen at large angles from the surface normal.

**Fig. 16.** Geant4 simulations of proton albedo from wet versus dry regolith. We show the fractional difference between wet regolith simulations and dry regolith simulations with a linear color scale.
shown, the neglect of GCR heavy ions leads to underestimation of neutron emission from the regolith at depth. Therefore, the tertiary proton excess visible in Fig. 17 is likely a significant underestimate of the albedo proton yield from a hydrated layer.

6. Conclusion

We show recent CRAter observations, simulations and laboratory measurements indicating how the proton albedo responds to the composition of the regolith. The observed latitude trend in the proton albedo in the lunar highlands shows an excess of the proton albedo near the poles that cannot be accounted for by heavy ion abundances in the regolith. Statistical methods reveal not only the significance of the trend with latitude, but also the predominance of the polar regions in increasing the albedo proton yield. One scenario that can potentially account for the observed latitude distribution of the proton albedo is the existence of hydrated material within regolith extending down to ∼10 cm.

Beam runs demonstrate the importance of nuclear evaporation and forward scattering in the magnitude of the proton albedo. However, a third effect appears to be playing an important role at energies > 15 MeV in albedo protons that causes an enhancement in protons emitted by the regolith. Upward directed neutrons emitted from nuclear evaporation are likely colliding with H nuclei and forward scattering to generate an excess of tertiary protons. The effect appears prominently in Geant4 simulations, but requires further validation in future beam studies and better quantification in future simulations. Therefore, at this stage, only tentative conclusions can be drawn from the CRAter observations.

There are several approaches for better resolving the albedo proton trend with latitude. First, and perhaps most importantly, improved statistics will reduce uncertainty in the slope of the albedo proton yield with latitude. Currently, the uncertainty is ∼30% and several additional years of data could reduce the uncertainty to <20%. However, another factor contributes substantially to increased uncertainties. The background subtraction and altitude correction rely on an understanding of the angular distribution of the proton albedo. Recent tests involving spacecraft slae will dramatically improve our understanding of the angular dependence and thereby better resolve the altitude dependence and background contributions. These improvements may lead to reductions in systematic uncertainties to better resolve the latitude dependence of the albedo proton yield.

Thus, we show the possible sensitivity of albedo protons observed by LRO/CRAter to hydrated material within lunar regolith. These findings show that the CRAter instrument provides important measurements informing volatile distributions within regolith at the Moon and potentially, with similar sensors and observations, at other bodies within the Solar System.

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