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The first cosmic ray albedo proton map of the Moon

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1. Introduction

[2] The Lunar Reconnaissance Orbiter (LRO) has a comprehensive suite of remote sensing instruments for measuring mineral and elemental variations over the lunar surface [Chin et al., 2007]. Instruments on LRO have made compositional maps using infrared [Greenhagen et al., 2010], visible [Gustafson et al., 2010] and ultraviolet spectra [Hendrix et al., 2010; Denevi et al., 2011] as well as radar data [McAdam et al., 2011]. The LEND instrument has also produced lunar surface compositional maps using the energy spectra of lunar neutrons [Mitrofanov et al., 2010; Crites et al., 2011]. The purpose of this paper is to present the first map of high energy protons emitted from the surface of the Moon as observed by the CRaTER instrument on LRO.

[3] Neutrons emitted from the Moon are produced by the impact of galactic cosmic rays (GCRs), extremely energetic ions from outside the solar system which are capable of fragmenting atomic nuclei (spallation) in the lunar regolith. Fragments from these collisions can themselves collide with and break apart additional nuclei, thus producing a shower of energetic protons, neutrons and other subatomic particles radiating away from the incident path of the parent ion. This phenomenon is analogous to galactic cosmic ray air showers which occur in the Earth’s atmosphere, albeit with smaller length scales due to the higher density of regolith. Some of the secondary particles produced by these collision cascades are ejected upwards out of the regolith, becoming “albedo” particles [Ulmer, 1994; Dorman, 2004; Spence et al., 2010].

[4] The LEND instrument on LRO and the Neutron Spectrometer on the earlier Lunar Prospector mission both used albedo neutrons to produce maps of compositional variations of the lunar surface. Both instruments detected a reduction in the neutron flux at certain energies near the lunar polar regions, indicating a higher abundance of hydrogen in the soil there than at lower latitudes [Feldman et al., 1998; Lawrence et al., 2006; Mitrofanov et al., 2010]. This hydrogen presumably
Figure 1. Diagram of CRaTER instrument showing cross-sectional cutaway view of the stack of six detectors (D1–D6) and pieces of tissue equivalent plastic (TEP). Example particle trajectories are shown for a high-energy galactic cosmic ray from the zenith passing completely through the instrument (red line) and for an albedo proton (blue line) coming up from the lunar surface and passing through four detectors before being stopped in one of the blocks of TEP. (Adapted from Spence et al. [2010].)

exists in the form of ancient water ice in or near cold permanently shadowed craters [Feldman et al., 1997, 2001; Elphic et al., 2004; Lawrence et al., 2011a]. LRO and Lunar prospector also measured variations in albedo neutron fluxes that are indicative of rough compositional differences in the regolith between the maria and highland regions [Feldman et al., 1998; Gasnault et al., 2001; Maurice et al., 2004; Crites et al., 2011; Lawrence et al., 2011b]. These spatial variations in albedo particle fluxes demonstrate that lunar-impacting GCRs and the upward-moving secondaries that they produce constitute a type of natural sounding experiment which can provide information on the elemental abundances in the top meter of lunar regolith. This paper reports on a search for an analogous effect in albedo protons, which are also emitted from the Moon as a result of GCR spallation.

3. Data Preparation

Several culling steps are required to extract D4 + D6 proton detections from the raw CRaTER data stream. CRaTER detects on average about ~six million events per day, of which only about ~200,000 per day qualify as simultaneous detections by D4 and D6 that we need for this study. Second, LRO is not always oriented with its instrument suite pointed at lunar nadir (D6 pointed at the Moon), and data gathered at orientations greater than one degree from nadir pointing are rejected. Third, the CRaTER instrument performs periodic calibration sequences during which artificial GCR detections are registered, so we reject these periods of time. Finally, we must determine the fraction of valid D4 + D6 events that are known with high certainty to be protons. This final identification step is the most complex one, as discussed in the remainder of this section.

A GCR that passes through two detector pairs must also traverse the TEP that lies between them, and because the plastic absorbs some of the GCR’s energy, the detector pairs on either end of the path will register unequal amounts of energy deposited in the detectors; this makes it possible to determine which direction the GCR was traveling. (The microsecond time resolution of the detector measurement electronics is much too slow to observe a difference in arrival times at different detectors.)

For this study we choose to look at GCRs which passed through the thick detectors of the Moon-facing and central detector pairs, designated as D6 and D4, respectively. The thick detectors are more sensitive to protons than the thin ones, and coincident detections in D4 + D6 cover the widest field of view of any two thick detectors. The D4 + D6 coincidence pair allows us to differentiate energetic protons coming from zenith (primary GCR from deep space) and from nadir (secondary albedo protons from the Moon). Since the larger piece of TEP partially shields D4 from GCRs arriving from the zenith direction, the sensitivity to primary GCRs just above the threshold energy of 60 MeV is somewhat reduced relative to the secondaries from the Moon, which have nearly unobstructed access to D6.
slower protons arriving from the Moon impact D6 first, are slowed in the TEP, and then deposit more energy in D4 than D6; this population is the horizontal branch labeled in Figure 2. This process by which energetic particles lose energy as a function of their charge, energy, and speed, as they pass through matter is given by the Bethe-Bloch equation (see Section 3.1.2 of Spence et al. [2010], for the application of this principle to the CRaTER instrument).

Also visible in Figure 2 are events which fall on D4 + D6 energy channel pairs in-between those of GCR species. These events are more uniformly distributed across channels, but are also concentrated near both axes. Preliminary analysis indicates that these events are caused by ions that miss D4 and/or D6 but produce electromagnetic and/or nuclear showers in the material of the sensor. Given the gradual falloff in this diffuse background source with increasing deposited energy, it follows that some of the events in the (D4, D6) channel pairs where protons are expected to register are not necessarily caused by protons. Since there is no way to distinguish a normal proton detection event from an event in the diffuse background population that registers at the same (D4, D6) channel pair, we must calculate the probability that each D4 + D6 event is a proton that passed through both detectors normally.

To calculate the probability that a D4 + D6 detection in a given channel pair is a proton, we statistically subtract the diffuse background source described in the previous paragraph from the data and then divide the resulting 2-D histogram by the original 2-D histogram. We first fit a 2-D surface to the regions to either side of the proton branches in order to characterize the shape of the diffuse source. We then subtract that fitted surface from the entire 2-D histogram plot, leaving an image of the proton branch which more accurately shows the number of proton events at each channel pair. Then, dividing the “proton only” histogram by the original uncorrected histogram yields a 2-D image of the probability that an event at a given channel pair is in fact a proton. A value of “0” on this image corresponds to (D4, D6) pairs where zero protons were recorded; all events there are from the diffuse source. A value of “1.0” would correspond to a (D4, D6) channel pair where only protons were recorded with no background events, but the diffuse source exists throughout (D4, D6) space, so there are no channel pairs with a proton probability of exactly 1.0. Figure 3 shows the region of the D4 + D6 proton probability plot where the lunar proton branch lies; the plot for the GCR proton branch looks similar but with somewhat higher probabilities.

The procedure of determining the magnitude of the diffuse background source introduces a significant systematic uncertainty into this study. We performed hundreds of trials of fitting functions to the diffuse background histogram, each with slightly different parameters, in order to estimate the systematic uncertainty introduced by not knowing exactly how much of the diffuse source contributes to the signal in the proton “branches” in the D4 + D6 histogram. Note that any over-estimation or under-estimation of the diffuse background source results in a corresponding under-estimation or over-estimation of both GCR protons and lunar albedo protons at

Figure 2. Two-dimensional histogram of D4 + D6 coincident detection events. Axes are labeled with the energy deposited in the central thick detector (D4) and lunar-facing thick detector (D6). Events lying along the diagonal extending from the lower-left to the upper-right are from particles with the highest incident energy and correspondingly lowest energy deposition in the detectors. Branches extending upwards from the diagonal are lower-energy particles arriving from space, while the single horizontal branch extending to the right represents protons arriving from the Moon. A diffuse background source which is spread over a wide area of channel pairs is also indicated.

Figure 3. Color-coded plot of the probability that D4 + D6 coincident events are lunar protons which passed through both detectors.
all times and at all locations on the Moon, so while this uncertainty applies to the absolute yield of albedo protons per GCR proton, it does not affect the uncertainties in the relative yields from month-to-month or from location-to-location on the Moon.

The protons which we have isolated here have incident energies of between 60 MeV and about 150 MeV. Protons with energies below 60 MeV are unable to pass completely through the TEP that lies between D4 and D6, and thus do not pass the requirement of coincident detections in D4 and D6. On the other hand, protons with energies greater than about 150 MeV deposit too little energy in D4 and D6, and register in channel pairs below ~1 MeV of deposited energy where lunar protons, GCR protons and GCR alpha particles all overlap.

4. Albedo Proton Yield

4.1. Yield Magnitude

The spallation yield of protons from GCRs impacting the lunar surface is the average number of protons which escape from the lunar surface for each impacting GCR. All albedo particles necessarily have lower energies than their parent impacting GCRs, so a determination of the absolute albedo proton yield from the Moon would require simultaneous measurements of GCRs and albedo particles covering several orders of magnitude of energy. Since we only have access to a limited portion of the GCR and albedo proton energy spectra in this data set (60 MeV to 150 MeV) we cannot compute an absolute yield. The GCR protons that we detect produce albedo particles with energies well below 60 MeV, which is too low for a D4 + D6 detection, and most of the albedo protons that we do detect were produced by GCR protons with energies well in excess of 150 MeV, which is too high for our method to distinguish the direction of arrival. Thus our best available option with the data at hand is to calculate the ratio of lunar protons to GCR protons for the energy ranges that we have access to. Because solar wind modulation causes the GCR spectrum to rise and fall at all energies, albeit with energy-dependent magnitudes [e.g., Parker, 1958] this calculated ratio will increase or decrease in the same sense as the actual yield of albedo protons to GCRs, but not proportionately.

4.2. Yield Map

Since CRaTER is simultaneously detecting upward-moving albedo protons and downward-moving GCR protons at all times, the most straightforward representation of the relative yield is the ratio of these two detected populations. To make a map, we define latitude/longitude pixels or areas of interest, sum the GCR and lunar protons detected over each pixel or area, and then take the ratio of the lunar to GCR protons to represent the relative yield. This method conveniently corrects for temporal changes in the GCR flux [e.g., Owens and Jokipii, 1973; Mulligan et al., 2009; Jordan et al., 2009; Schwadron et al., 2010] which would have modified the albedo proton flux detected by LRO. Figure 4 shows the resulting map of this ratio for spatial resolutions of 10 degrees and 15 degrees.

Since the actual and measured albedo proton yields are expected to change over time as solar activity modulates the GCR proton spectrum, there is the potential problem that a temporal change in the yield will manifest itself as a spatial feature in the yield map. However, as the Moon rotates under LRO’s polar orbit, LRO sweeps over all lunar longitudes in only two weeks, so that the modulations in the background GCR rate are slow relative to the mapping time scale. In addition, theory [Huang et al., 2009] and data [Case et al., 2010] both indicate that lunar phase modulation of GCRs is not significant.

Figure 4. Cylindrical projection albedo proton maps of the Moon at two spatial resolutions: (top) 15 degrees and (bottom) 10 degrees. Colors represent the ratio of lunar protons to GCR protons, from red (high) to blue/purple (low).

Figure 5. Histogram of albedo proton/GCR proton ratio for 10-degree binning of cylindrical projection map, compared to 100 simulated flat maps. The simulations randomly distribute 330,000 lunar protons (the same number as in the data) over the lunar map to mimic what CRaTER would be expected to measure for a perfectly uniform lunar/galactic proton ratio.
The maps of the ratio of albedo protons to GCR protons in Figure 4 are consistent with a spatially uniform albedo proton yield, meaning regions of apparently high and low yield are merely artifacts of the counting statistics. A brief inspection of the two resolutions in Figure 4 reveals that high and low yield pixels in one map are not necessarily pronounced in the other. Indeed, the histogram of yield values is entirely consistent the counting statistics of 330,000 lunar protons produced by a surface with a spatially uniform yield, as demonstrated by the simulated measurements of 100 flat maps shown in Figure 5.

Dividing the lunar surface into a few large regions gives similarly uniform results. As shown in Table 1, the yield at the lunar poles is essentially identical to the average yield over the rest of the surface, while the difference in yields between the maria regions and highlands is larger but still within statistical uncertainty. These results are consistent with preliminary Geant4 (see Allison et al. [2006] for a description of Geant4) simulations that show systematic but extremely small differences between the albedo proton spectra coming from maria, highlands, or pure water ice at energies detected by CRaTER.

### 4.3. Time-Dependent Variations

Figure 6 shows the monthly averaged time variation in the GCR rate, albedo proton rate, and spallation yield. Detection rates decreased significantly over the 19 months of this study, as expected given the increase in solar activity which occurred over this span of time [e.g., Schwadron et al., 2010]. The relative spallation yield jumped about 8% in just two months (February to April, 2010) and has gradually increased since then. The most likely explanation for this is that as solar activity has increased, the lowest-energy GCRs have been preferentially excluded from the inner solar system, meaning only the more energetic GCRs (which produce more albedo protons particle-for-particle within the range of energies that we’re measuring) are still reaching the Moon at the same rate [e.g., Webber and Lezniak, 1974]. As CRaTER sees only a portion of the GCR spectrum, we cannot directly verify that the average GCR energy has increased, though

<table>
<thead>
<tr>
<th>Region</th>
<th>Maria/Highlands</th>
<th>Poles/Low-Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative yield</td>
<td>1.006 ± 0.006</td>
<td>1.001 ± 0.007</td>
</tr>
</tbody>
</table>

### Figure 6

Time variation of (top) cosmic ray protons, (middle) lunar protons, and (bottom) the ratio of lunar to cosmic ray protons. Error bars for the month-to-month statistical uncertainty are shown separately from the systematic calibration uncertainty which does not affect the shapes of the plots.
preliminary studies do indicate that the linear energy transfer spectrum has changed over this time period.

5. Discussion

Within statistical uncertainty, we have found no significant difference in the proton spallation yields from different regions on the Moon. This is consistent with predictions from preliminary modeling results which suggest that any real yield variations are simply too small to be detected in this data set.

We calculate a global average ratio of lunar protons to galactic cosmic ray protons of 0.38 ± 0.02 for D4 + D6 detections with incident energies between 60 MeV and ~150 MeV; this ratio is up to three times larger than balloon-borne measurements of “splash albedo” protons made in the Earth’s upper atmosphere. Murayama [1967] calculated ratios at Earth of between 0.3 and 0.4 for albedo particles with energies above 75 MeV, but this included all charged albedo particles, meaning the ratio for protons alone was smaller. McDonald’s [1958] measurements of primary and albedo protons at Earth suggest a ratio of ~0.13 for protons with energies between 100 and 300 MeV, while Verma [1967] derived albedo-to-primary proton ratios of 0.15 at Earth for energies between 90 and 200 MeV. The ratio calculated in this work for the Moon must inevitably be higher than the real ratio, since the larger of the two pieces of TEP partially shields both D4 and D6 from the lowest energy GCRs arriving from space, thus reducing the detection efficiency of GCRs coming from the zenith and increasing the measured ratio of albedo-to-source protons. Correcting for this partial shielding would not be trivial, as the GCR spectrum is not known precisely, and the modification of the spectrum depends on both the angle of incidence and location of impact of each galactic cosmic ray on the CRaTER instrument. Regardless, given that the necessary correction would increase the GCR flux from zenith and decrease the ratio, such a correction would reduce the lunar ratio to a value closer to those measured at Earth.

The total flux of GCRs and albedo protons has been decreasing since 2009, as expected for a period of increasing solar activity. If the Sun is entering a multidecadal “grand minimum” period as suggested by some studies [Feulner and Rahmstorf, 2010; Miyahara et al., 2010], then the solar cycle-averaged flux of GCRs and of all albedo particles from the Moon should be higher for the foreseeable future than it was during the previous five decades. This may have implications for any future human colony on the Moon, both in terms of radiation dose for astronauts [e.g., Schwadron et al., 2010] and decade-scale space weathering of materials [Schwadron et al., 2012].

The average global spallation yield from the Moon jumped significantly in March and April of 2010, and has been increasing more gradually since then, indicative of the increase in solar activity and corresponding reduction in lower energy galactic cosmic rays relative to higher energy ones. This is an expected result, as higher energy GCRs should result in higher spallation yields from unprotected planetary surfaces than lower energy GCRs.

We conclude that galactic cosmic rays generate a proton albedo that depends primarily on the intensity and energy spectrum of the incident high energy particles. The map of lunar albedo protons reveals apparent uniformity over the lunar surface with little or no variability due to the target composition and surface properties. This is consistent with early modeling results that predict finite but small differences in albedo proton yield at these energies owing to GCR interactions with different surface minerals; accumulation of additional observations may improve statistics enough to reveal an expected but weak albedo proton signal.

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References


