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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 half 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 (Papike 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

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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_2O (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 μm on the lunar surface. These features indicated the presence of materials containing OH and H_2O. 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_2O 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 3 μm 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 μm) 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

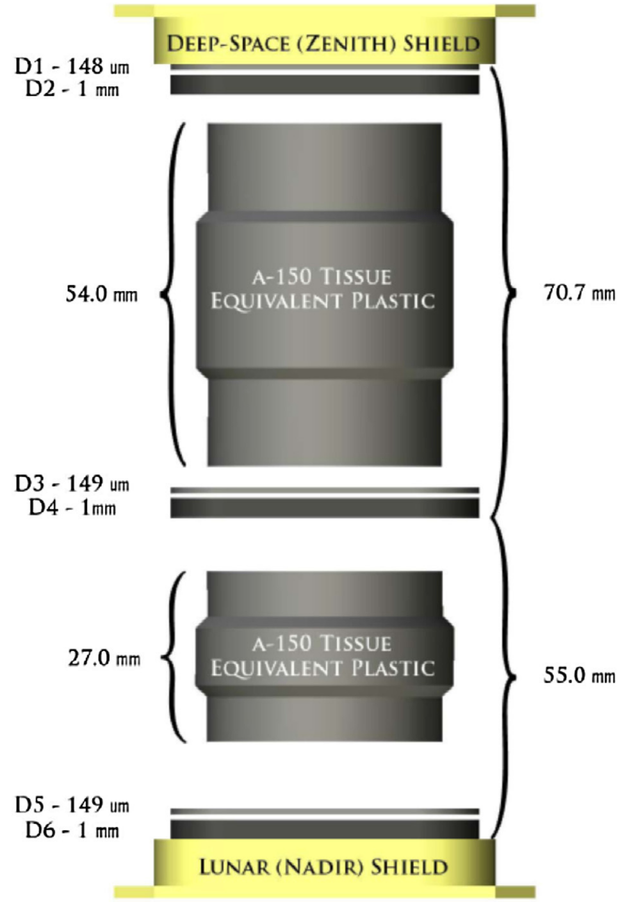

Fig. 1. The CRaTER instrument measures >12 MeV/nuc particles in 6 detectors (D1–D6) with Tissue Equivalent Plastic (TEP) between pairs of detectors. Thick and thin detectors with different gains allow a large range of Linear Energy Transfer (LET) to be sampled. TEP mimics absorption of energy by human tissue as radiation passes through the telescope. In the nominal spacecraft orientation, the instrument measures particles from zenith and nadir directions. The yellow “shields” at the top and bottom of the instrument are in fact the holders for much thinner windows (30 mil Al). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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