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Hydrogen distribution in the lunar polar regions

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ABSTRACT

We present a method of conversion of the lunar neutron counting rate measured by the Lunar Reconnaissance Orbiter (LRO) Lunar Exploration Neutron Detector (LEND) instrument collimated neutron detectors, to water equivalent hydrogen (WEH) in the top ~1 m layer of lunar regolith. Polar maps of the Moon's inferred hydrogen abundance are presented and discussed.

1. Introduction

Whether or not water ice is present at the lunar poles continues to be both a scientifically intriguing question and an important factor for any future human exploration of the Moon. Prior to the 1960s, the Moon was believed to be anhydrous. However, in the beginning of the 1960s theoretical studies showed that water and other hydrogen-bearing volatiles could be stable in cold traps near the lunar poles (Watson et al., 1961). There may be several sources for hydrogen-bearing volatiles: they may either slowly leak from the lunar interior over billions of years, be delivered to the lunar surface by comets and asteroids, or be produced by the bonding of solar wind protons (H^+) with oxygen in regolith silicates to form hydroxyls (OH^-) and possibly water ice. Near surface hydrogen-bearing volatiles may be diurnally transient by thermally induced jumping from hot surfaces near local noon that result in accumulations towards cooler surfaces near the dawn terminator or poles (Vasavada, et al., 1999; Starukhina and Shkuratov, 2000; Crider and Vondrak, 2000, 2003).

The first putative detection of water ice deposits on the lunar South Pole was observed by the Clementine – Bistatic Radar Experiment (Nozette et al., 1996). However, subsequent studies of the Circular Polarization Ratio (CPR) by Arecibo radar (Stacy et al., 1997) and by Mini-RF Synthetic Aperture Radar on board the Lunar Reconnaissance Orbiter (LRO) (Nozette et al., 2010) did not identify any significant evidence for the presence of water ice (Campbell et al., 2003; Thomson et al., 2012). Also, due to the low contrast of the dielectric permittivity between water ice and silicate regolith, it will be difficult to use CPR to identify ice mixed with the lunar regolith (Fa et al., 2011).

The Lunar Prospector Neutron Spectrometer (LPNS) observed more definitive evidence of hydrogen-bearing volatiles at the Moon's poles in 1998. Results from LPNS indicated that the flux of epithermal lunar neutrons (0.4 eV–100 keV) is suppressed by about 5% towards both poles above ±75° latitude in comparison with the average flux at middle latitudes. This polar neutron suppression was attributed to hydrogen-bearing volatiles or water ice within the top 1 m of the regolith (Feldman et al., 1998). Analysis of observations was not able to adequately distinguish the polar permanently shadowed regions (PSRs) since the uncollimated LPNS spatial resolution had a Full-Width at Half-Maximum (FWHM) of 130 km and 45 km for the high and low altitude mission segments,

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respectively (Maurice et. al., 2004). To better quantify the role of the PSRs, the Pixon image reconstruction algorithm was applied to the LPNS observations with an a priori assumption that the enhanced hydrogen concentrations are constrained to the PSRs (Teodoro et al., 2010). Those results showed that the LPNS observations are consistent with the assumption that the PSRs are responsible for the strong suppression of epithermal neutron flux. However, such a model-dependent test was not able to prove that PSRs are responsible for the neutron suppression. The estimated concentration of hydrogen in the PSRs corresponded to ~1 wt% water.

Near infrared (NIR) spectroscopy of the dayside lunar surface has been performed by three independent sets of observations. The Moon Mineralogy Mapper (M^3) onboard Chandrayaan-1 (Pieters et al., 2009), the High-Resolution Instrument-Infrared spectrometer (HRI-IR) onboard Deep Impact (Sunshine et al., 2009), and the Visual and Infrared Mapping Spectrometer (VIMS) onboard Cassini (Clark et al., 2009) all showed a clearly enhanced absorption of the 3 μm band in near-infrared (NIR) spectra. This spectral feature indicates the presence of OH^- (2.81 μm), H_2O (2.95 μm), and hydrated minerals (3.14 μm), corresponding to the equivalent of ~0.3 wt% of H_2O concentrated in the upper 1–2 mm of surface regolith. Sunshine et al, (2009) also showed that surface hydration depends on the local solar time. This finding supports the idea that OH^- and H_2O molecules may exist in the lunar exosphere and migrate across the lunar surface during the day and stay in a subsurface layer during the lunar night (Crider and Vondrak, 2000, 2003). Thus, NIR observations have substantiated the conclusions from neutron observations that the content of hydrogen in the regolith increases towards the poles (McCord et al, 2011), but the details of the spatial hydrogen distribution in the Moon's polar regions remained uncertain, and, most importantly, the direct correlation of the PSRs to water ice deposits remains unproven.

Based on these initial observations, the Lunar Reconnaissance Orbiter (LRO) mission science requirements were formulated (Vondrak et al., 2010). One of these requirements is to perform high spatial resolution mapping of hydrogen deposits at the Moon's poles as well as reconnaissance of the putative near-surface water ice deposits.

The Lunar Exploration Neutron Detector (LEND) was selected by NASA to directly address this requirement. LEND is currently operating onboard the LRO spacecraft and is able to independently detect the presence of hydrogen in the top ~1 m of lunar regolith. LEND was provided by Russia in accordance with the bilateral Roscosmos-NASA agreement (Mitrofanov et al., 2010a). LEND's neutron collimator design achieves a spatial resolution of ~10 km for measurements of the lunar surface epithermal neutron emission from an orbit of a 50 km altitude. High-resolution maps from LEND observations have confirmed the polar suppression of epithermal neutron flux. In addition to the general epithermal neutron flux suppression around the poles, neutron suppressed regions (NSRs) were also detected in lunar regions that receive occasional solar illumination (Litvak et al., 2012a; Mitrofanov et al., 2012; Boynton et al., 2012). These NSRs are indicative of enhanced hydrogen content and are consistent with the existence of water ice deposits < 1 m in depth below the lunar surface. Such a finding may indicate that water ice exists in the regolith under a thin dry regolith layer, that is periodically illuminated by sunlight, but thermally isolates a buried water ice layer. The thickness of the uppermost isolating layer could be rather small (about several centimeters) and may be negligibly small in comparison with the thickness of the buried water ice layer. Only some of the largest PSRs demonstrate significant neutron suppression relative to the local vicinity (Sanin et al., 2012; Boynton et al., 2012), but many other PSRs do not contain any significant *additional* concentrations of hydrogen in comparison with the sunlit areas around them. An enhancement of hydration in craters' pole-facing slopes was found using the LEND data (McClanahan et al., 2014). Diurnally varying surface hydration may also be occurring on a global scale (Livengood et al., 2015; McClanahan et al., 2015).

Clear evidence of the presence of hydrogen-bearing volatiles (H_2O, H_2S, NH_3, C_2H_2, CH_3OH, CH_4, OH^-) on the Moon was observed by the LRO companion mission – the Lunar CRater Observing and Sensing Satellite (LCROSS) (Colaprete et al., 2010). NIR and ultraviolet (UV) observations made by LRO and LCROSS, of the ejected plume resulting from the impact of LRO's launch vehicle upper stage into the permanently shadowed region in Cabeus crater indicated 5.6 ± 2.6 wt% water ice in Cabeus. This value is consistent with the LEND estimate of water in Cabeus, which was made using the orbital data with the assumption of a 60 cm thick upper layer of low H content (Mitrofanov et al., 2010b).

The Lyman Alpha Mapping Project (LAMP) instrument onboard LRO performs observations using UV radiation from stars as well as the Sun's Lyman-α emission scattered from interplanetary hydrogen atoms. LAMP has shown that some large area PSRs in polar craters (like Shoemaker, Haworth, Faustini, and Cabeus) typically have a low UV albedo, which is consistent with a 1–2 wt% water frost layer in the upper micron of the lunar regolith (Gladstone et al., 2012; Hayne et al., 2015). Evidence of diurnal surface hydration was also detected by LAMP observations based on a local minimum in hydration at noon, and hydration increasing approximately symmetrically toward the terminators (Hendrix et al., 2012).

2. LEND instrumentation and data reduction

The LRO spacecraft was launched on 18 June 2009 and began its primary science mapping phase on 15 September 2009. At that time, the spacecraft had a circular polar orbit with ~50 km altitude, and covered the entire lunar surface in one lunation. In December 2011, the spacecraft was transitioned to a dynamically stable elliptical orbit to save fuel and to maximize its operating lifetime. LRO continues its operations in this orbit today. The pericenter of the orbit ranges between 30 and 60 km in altitude near the South Pole.

LEND has nine neutron detectors to measure the lunar leakage neutron flux (in several energy bands) that is produced by high energy cosmic rays interacting with lunar regolith nuclei. Eight detectors are based on identical proportional counters developed by LND Inc. (LND 253123 type), filled with ^3He gas at 20 atmospheres pressure. These counters detect thermal and epithermal neutron flux with ~100% efficiency at energies below 10^{-1} eV, that decreases by a factor of 10 at ~500 eV (Litvak et al., 2012b). Four of the detectors (Collimated Detectors of Epithermal Neutrons, CSETN1-4) are installed inside a neutron collimation module composed of polyethylene and ^{10}B layers. The collimator's nadir pointing aperture is open to the detector forming the instrument's field of view (FOV) of 5.6° (Mitrofanov et al., 2008; Litvak et al., 2016).

The orientation of the LRO spacecraft is generally maintained in the nadir direction to allow the mapping of the lunar surface by its complement of on-board instruments. LEND's observations are optimal when nadir pointing, and the front sides of four cylindrical CSETN detectors inside the collimator are directed to the sub-spacecraft point on the lunar surface. The collimator shields the CSETN detectors from incident thermal and epithermal neutrons sourced from large off-nadir angles (14°–75°), and allows detection of the lunar neutrons coming in with angles 0°–14° of the nadir direction. The front sides of the CSETN detectors are covered by 0.5 mm thick Cd foil to absorb neutrons with energies <0.4 eV. Thus, these detectors are primarily sensitive to the lunar epithermal neutrons with energy >0.4 eV coming within a 0–14°