Icarus 255 (2015) 88–99

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Evidence for the sequestration of hydrogen-bearing volatiles towards the Moon's southern pole-facing slopes

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ARTICLE INFO

Article history:
Received 14 February 2014
Revised 27 September 2014
Accepted 2 October 2014
Available online 19 October 2014

Keywords:
Moon
Ices
Moon, surface
Regoliths

ABSTRACT

The Lunar Exploration Neutron Detector (LEND) onboard the Lunar Reconnaissance Orbiter (LRO) detects a widespread suppression of the epithermal neutron leakage flux that is coincident with the pole-facing slopes (PFS) of the Moon's southern hemisphere. Suppression of the epithermal neutron flux is consistent with an interpretation of enhanced concentrations of hydrogen-bearing volatiles within the upper meter of the regolith. Localized flux suppression in PFS suggests that the reduced solar irradiation and lowered temperature on PFS constrains volatility to a greater extent than in surrounding regions. Epithermal neutron flux mapped with LEND's Collimated Sensor for Epithermal Neutrons (CSETN) was analyzed as a function of slope geomorphology derived from the Lunar Orbiting Laser Altimeter (LOLA) and the results compared to co-registered maps of diurnally averaged temperature from the Diviner Lunar Radiometer Experiment and an averaged illumination map derived from LOLA. The suppression in the average south polar epithermal neutron flux on equator-facing slopes (EFS) and PFS (85–90°S) is 3.3 ± 0.04% and 4.3 ± 0.05% respectively (one-sigma-uncertainties), relative to the average count-rate in the latitude band 45–90°S. The discrepancy of 1.0 ± 0.06% between EFS and PFS neutron flux corresponds to an average of ∼23 parts-per-million-by-weight (ppmw) more hydrogen on PFS than on EFS. Results show that the detection of hydrogen concentrations on PFS is dependent on their spatial scale. Epithermal flux suppression on large scale PFS was found to be enhanced to 5.2 ± 0.13%, a discrepancy of ∼45 ppmw hydrogen relative to equivalent EFS. Enhanced poleward hydration of PFS begins between 50°S and 60°S latitude. Polar regolith temperature contrasts do not explain the suppression of epithermal neutrons on pole-facing slopes. The Supplemental on-line materials include supporting results derived from the uncollimated Lunar Prospector Neutron Spectrometer and the LEND Sensor for Epithermal Neutrons.

1. Introduction

After years of research the ongoing quest to quantify the spatial distribution of the Moon's hydrogen-bearing volatiles remains an intriguing and open question for lunar scientists. The long standing objective to understand the nature of volatiles and their surface distributions comes from the ongoing in-situ resource knowledge gaps that must be addressed to effectively plan future lunar surface missions (Lofgren, 1993; Sanders and Larson, 2010). For decades there was a polar focus, driven by the dominant theory that held that the Moon's extreme vacuum and thermal conditions precluded the near-surface existence of hydrogen-bearing volatiles, except in the cryogenically stable permanently shadowed regions (PSR) (Urey, 1952; Watson et al., 1961; Arnold, 1979). These studies suggested hydrogen-bearing volatiles could be cold-trapped in the PSR's and accumulated over billions of years of lunar history by the combined effects of highly constrained sublimation rates and

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http://dx.doi.org/10.1016/j.icarus.2014.10.001
0019-1035/Published by Elsevier Inc.

the episodic influx of meteorites or comets. However, in 2009 discoveries from the Chandraayan-1, Deep Impact and Cassini missions forced scientists to consider the possibility of a much more complicated volatile environment in which hydrogen-bearing volatiles are more prevalent and active on the lunar surface than previously thought (Goswami and Annadurai, 2008; Pieters et al., 2009; Clark, 2009; Sunshine et al., 2009). Their jointly released results from near infra-red (NIR) spectroscopy of the 3 μm absorption line associated with hydroxyl and/or water suggested that there is an active and widespread hydration of the lunar surface. Exogenously sourced hydroxyl and water may be produced on the lunar surface by solar wind driven and proton-induced hydroxylation of regolith silicates that may be subsequently ballistically transported in bombardment processes (Starukhina, 2000; Crider and Vondrak, 2000, 2002; McCord et al., 2011). From these results, the static, PSR-centric perspective of lunar hydrogen volatiles is now evolving to comprehend new and more complex dynamics that have and are driving the Moon's hydrogen-bearing volatiles.

Several results have partially proven the PSR hypothesis. Initial Clementine bistatic radar observations of the poles were inconclusive that found surface circular polarization ratios that were consistent with an interpretation of water ice in some PSR's, but were later refuted (Nozette et al., 1996; Simpson and Tyler, 1999; Fa et al., 2011). Results from the late 1990's era Lunar Prospector Neutron Spectrometer (LPNS) showed, using image reconstruction techniques applied to epithermal neutron flux maps, that some south polar PSR's had regional signatures of enhanced concentrations of hydrogenous materials (Feldman et al., 1998; Elphic et al., 2007). More recently, the Lunar Reconnaissance Orbiter's (LRO) Lunar Exploration Neutron Detector (LEND) found significant suppressions in the epithermal neutron flux consistent with hydrogen-bearing materials within the PSR's of several craters e.g. Cabeus and Shoemaker (Chin et al., 2007; Vondrak et al., 2010; Mitrofanov et al., 2010a, 2010b; Boynton et al., 2012; Sanin et al., 2012). Far ultra-violet (FUV) observations of the Moon's polar Lyman-α albedo by LRO's LAMP instrument suggested ~1–2% water frost on the regolith of several south polar PSR's (Gladstone et al., 2012). Results from LRO's Lunar Observing Laser Altimeter albedo (LOLA) were used to suggest deposits of surface water frost on the walls of Shackleton crater using 1064 nm albedo measurements (Smith et al., 2010; Zuber et al., 2012). Lucey et al. (2014) found LOLA albedo differences that are consistent with an interpretation of water frost deposition in PSR vs. non-PSR and on pole-facing slopes (PFS) vs. equator-facing slopes (EFS). Ground truth evidence of the existence of hydrogen-bearing materials within a south polar PSR was established by the NIR and ultra-violet (UV) detection of water and molecular hydrogen within the excavated plume made by the exhausted rocket motor of the Lunar CRater Observing and Sensing Satellite (LCROSS) as it impacted Cabeus crater (Colaprete et al., 2010; Hurley et al., 2012).

Several lines of evidence support the hypothesis that surface hydration may be occurring outside the PSR's. Theoretical studies suggest that the extreme end-member cryogenic temperatures <100 K in the polar PSR's may be not provide the optimal thermal conditions for the entrainment of hydrogen-bearing volatiles (Siegler et al., 2011; Schorghofer and Taylor, 2007). LEND found that the epithermal neutron flux was significantly suppressed in some polar regions outside PSR's, inferring the presence of hydrogen-bearing materials in regions that regularly experience some level of solar irradiation (Mitrofanov et al., 2012). Beginning in the mid-latitudes, results from NIR spectroscopy, far ultra-violet (FUV) and epithermal neutron observations indicate trends that are consistent with the interpretation poleward increases in hydrogen concentration (Feldman et al., 1998; McCord et al., 2011; Gladstone et al., 2012; Litvak et al., 2012; Hendrix et al., 2012; Li et al., 2012). From LEND results, Mitrofanov et al. (2012) postulated a correlation between the poleward decrease in the epithermal neutron flux and solar irradiation.

There is also evidence that topography, aside from the polar basins that contain the PSR's, has an active role in biasing the locations of volatile spatial distributions. NIR results from the Moon Mineralogy Mapper on Chandraayan-1 identified diurnally shifting hydrogen-bearing materials that moved through the day towards low illumination conditions on the slopes of mid-latitude craters (Pieters et al., 2009). Cheek et al. (2011) found evidence in NIR spectroscopy measurements that surface hydroxyl or water concentrations were enhanced in the upper latitude Golschmidt crater, 73°N 3.8°W. However, enhanced hydrogen concentrations were not detected in the analysis of LPNS epithermal neutron flux associated with Goldschmidt indicating the hydrogen deposits are likely associated with the top few microns of the surface (Lawrence et al., 2011).

This research explores the possibility that the Moon's topography creates locally stable pockets of hydrogen-bearing volatiles in the persistently low solar irradiation and temperature conditions found on PFS. Nearly ~4.5 years of high resolution observations from LEND's Collimated Sensor for Epithermal Neutrons (CSETN) collected over the Moon's south polar region at 30–50 km altitude are correlated with fully-registered topography and average illumination maps derived from LOLA as well as an average surface temperature map produced by the Diviner Lunar Radiometer Experiment (Diviner) (Paige et al., 2010a, 2010b). LOLA topography is decomposed as a function of the three principal factors that govern the Moon's insolation including: latitude, slope and slope aspect (Smith et al., 2010). By averaging the fully registered maps as a function of these primary insolation factors, the averaged areas are increased and the statistical significance of the results is enhanced. Localized contrasts of averaged epithermal neutron flux, illumination and temperature on pole and equator-facing slopes (EFS) illustrate their respective correlation to insolation.

This work shows that:

(a) The suppression of the epithermal neutron flux on PFS is substantially greater than on equivalent EFS, which supports the hypothesis that local concentrations of hydrogen are biased towards PFS.
(b) The biased hydration of PFS is a widespread phenomenon in the Moon's southern latitudes.
(c) The contrast between the EFS and PFS epithermal neutron flux and the inference for the hydration of pole-facing surfaces extends from about 50°S latitude to the south pole.
(d) The magnitude of the epithermal neutron flux suppression increases with the spatial scale of PFS, but not EFS in the upper-latitudes. The result suggests that a hydrogen contrast exists for PFS with respect to their surroundings and that EFS are hydrated to levels that are in equilibrium with their surroundings.
(e) Regolith temperature contrasts appear to be ruled out as the cause of the localized suppression of epithermal neutron flux on pole-facing slopes.

Section 2 reviews the paper's primary hypothesis and uses a Martian example to illustrate the characteristics of a pattern of hydration on crater slopes. The section also describes the implications for hydrogen detection by orbital neutron and temperature remote sensing of lunar slopes. Section 3 illustrates the south polar averaged epithermal neutron flux, temperature, illumination and topography maps used in this study. Analytical methods are also described. Section 4 reviews several results from the correlated studies of epithermal flux, illumination, topography and tempera-