

DIURNALLY VARIABLE HYDROGEN-BEARING VOLATILES AT THE MOON'S EQUATOR: EVIDENCE, CONCENTRATION, TRANSPORT, IMPLICATIONS. T. A. Livengood^{1,2,3}, G. Chin², R. Z. Sagdeev³, I. G. Mitrofanov⁴, W. V. Boynton⁵, L. G. Evans^{2,6}, M. L. Litvak⁴, T. P. McClanahan², A. B. Sanin⁴, R. D. Starr^{2,7} and J. J. Su³, ¹CRESST, Code 693, NASA Goddard Space Flight Center, Greenbelt, MD 20771, timothy.a.livengood@nasa.gov, ²NASA Goddard Space Flight Center, Greenbelt, MD, ³University of Maryland, College Park, MD, ⁴Institute for Space Research, Moscow, Russia, ⁵Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, ⁶Computer Sciences Corporation, Lanham-Seabrook, MD, ⁷Catholic University of America, Washington, DC.

The Lunar Exploration Neutron Detector (LEND) detects the presence of hydrogen on the night side of the Moon near the equator, peaking in concentration on the dayside of the dawn terminator and diminishing through the dawn-to-noon sector with minimum hydrogen in the mid-afternoon to post-dusk sector. The chemical form of detected hydrogen is not determinable from these measurements, but is expected to be in the form of water molecules or hydroxyl ions. LEND, on the polar-orbiting Lunar Reconnaissance Orbiter (LRO) spacecraft [1,2], detects hydrogen in the regolith through the localized suppression of epithermal neutron flux from the Moon's surface. The greatest flux suppression is at dawn, with the least suppression and least hydrogenation in the lunar afternoon to post-dusk sector. The minimum-to-maximum contrast is greater than 5σ . The peak concentration within the upper ~ 1 m of regolith is estimated to be 0.0125 ± 0.0022 weight-percent water-equivalent hydrogen (wt% WEH), yielding about 187 ± 33 ml recoverable water per cubic meter of regolith at dawn. The non-uniform distribution of hydrogen with respect to local time implies active volatile transport on the Moon at low latitudes. Volatiles are deduced to collect in or on the cold night-time surface, then distill out of the regolith after dawn as rotation exposes the surface to sunlight, achieving maximum dehydration in the afternoon. The liberated volatiles migrate away from the warm subsolar region toward the cold night-time surface beyond the terminator, resulting in maximum concentration at the dawn terminator. Since the water is naturally distilled from the regolith by sunlight every lunar day and restored to the cold regolith by adsorption every lunar night, a cold metal plate on the surface could intercept and collect up to the full peak concentration of 187 ml water per square meter of surface through every lunar night for *in situ* resource utilization (ISRU), with no expenditure of energy for distillation from mined regolith.

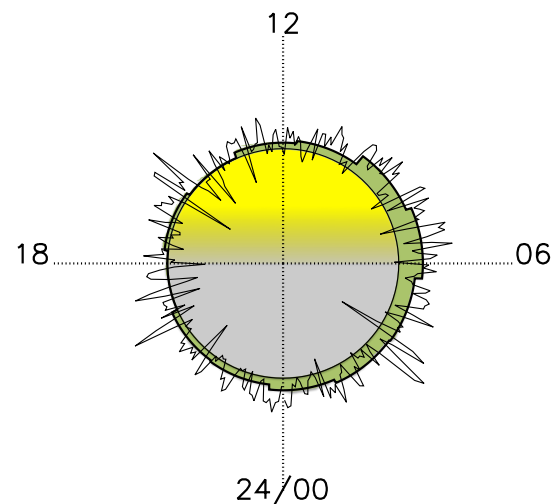


Fig. 1. Variable H distribution as a function of local time, deduced from LEND uncollimated epithermal neutron detector SETN. Volatiles that move east to the dusk terminator condense or adsorb in the surface overnight, then remobilize after dawn and migrate west to the cold dawn terminator, building up a local maximum of volatiles near dawn.

The implied concentration of volatiles is nontrivial. Previous detections of equatorial volatiles as hydroxyl or water in mineral hydration [3,4,5] could be accommodated by a skin layer only microns thick, but the volatiles detected by neutron remote-sensing are about four to five orders of magnitude greater in areal density. This is not a discrepancy between the measurements, as the observed mineral hydration can establish only a lower limit due to the uncertain depth of hydration. If the mineral hydration were estimated to extend even as much as millimeters deep, that would diminish the ratio between the measurements by about three orders of magnitude. Measurements of mineral hydration also have provided evidence for diurnally variable concentrations of adsorbed volatiles that maintain a local maximum at the dawn terminator [4]. Maintaining a region of maximum density in hydration that is fixed to the local time as the Moon rotates requires desorption from the surface and transport to the nightside cold trap faster than the Moon rotates, at

4.3 m/s, necessitating that volatile transport be accomplished by thermal desorption into free space above the surface, as a gas. Conservation of mass at the terminator between adsorbed volatiles in slow prograde rotation and desorbed volatiles in rapid retrograde transport across the terminator implies that less than 1% of volatiles present at the terminator are gaseous while more than 99% of the volatiles remain adsorbed within the regolith at that local time. This fractionation reconciles the lower limit quantity of observed variability in mineral hydration with the 10^7 mol/cm³ density of evanescent atmosphere estimated from lunar dawn measurements by the Apollo 17 LACE instrument [6], assuming the hydrated layer thickness were only 1-10 μ m.

Volatile concentrations detected by neutron remote-sensing remain about four orders of magnitude greater than the Apollo 17 estimate, even assuming that only 1% of volatiles at the terminator contribute to the detectable above-ground atmosphere. Solar ultraviolet photolysis lifetimes of molecules at Earth-Moon orbit are about 10^5 seconds [7]. Assuming that photolysis acts only on the fraction of volatiles that are above-ground at any given moment, effectively increasing the lifetime by two orders of magnitude, the required supply rate of new molecules to replace photolysed molecules and maintain equilibrium is about 5 orders of magnitude greater than the total solar wind delivery rate of about 2×10^8 p⁺/cm²/s at the Moon [8]. The estimated quantity of volatiles delivered by micrometeoroids is lesser, creating an even greater discrepancy. Although solar wind implantation and micrometeoroid impact processes will contribute to lunar volatiles, the only remaining delivery mechanism that has the potential to account for contemporary volatile equilibrium is outgassing from the Moon itself.

References: [1] Vondrak, R., *et al.* (2010). *SpaSciRev* **150**, 7–22, doi: 10.1007/s11214-010-9631-5. [2] Mitrofanov, I. G., *et al.* (2010). *SpaSciRev* **150**, 183–207, doi: 10.1007/s11214-009-9608-4. [3] Pieters, C. M., *et al.* (2009). *Science* **326**, 568–582, doi: 10.1126/science.1178658. [4] Sunshine, J. M., *et al.* (2009). *Science* **326**, 565–568, doi: 10.1126/science.1179788. [5] Clark, R. N. (2009). *Science* **326**, 562–564, doi: 10.1126/science.1178105. [6] Hoffman, J. H., and R. R. Hodges, Jr. (1975). *The Moon* **14**, 159–167, doi: 10.1007/BF00562981. [7] Budzien, S. A., and P. D. Feldman (1991). *Icarus* **90**, 308–318, doi: 10.1016/0019-1035(91)90109-7. [8] Crider, D. H., and R. R. Vondrak (2002). *AdvSpRes* **30**, 1869–1874, doi: 10.1016/S0273-1177(02)00493-3.