

COULD LUNAR ENDOGENIC HYDROGEN BE HIDING IN PLAIN SIGHT?

T. H. Prettyman¹, D. J. Lawrence², W. C. Feldman¹, ¹Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, prettyman@psi.edu, ²Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723.

Introduction: The bulk hydrogen concentration of the regoliths of the Moon, Vesta, and Mercury has been measured [1-3]. Hydrated materials on and within the regoliths of these airless, silicate bodies is thought to be largely exogenic [1-5]. Potential sources of hydrogen include solar wind, comets and volatile-rich meteoroids. On the Moon, permanently-shadowed polar craters act as cold traps, in which water ice can be stored for billions of years. Outside of the permanently shadowed regions, water-ice is not stable and the distribution of hydrogen is probably determined by space weathering [5,6]; however, hydrated minerals formed by the action of magmatic liquids in the lunar interior may also be present on portions of the surface.

Recently, [7] found evidence for magmatic OH (~10 ppm H) within the central peak of Bullialdus crater, which is rich in KREEP (Potassium, Rare Earth Elements and Phosphorus). Studies of lunar meteorites show that magmatic OH is bound to apatite in KREEP and other lunar materials [8,9]. During magma ocean crystallization, water and other volatiles is expected to concentrate in the last dregs of the magma ocean. Thus, OH-bearing apatite should be abundant in KREEP [5,9]. Paradoxically, apatites in mare basalt samples have higher concentrations of OH than KREEP-rich rocks, which may reflect the heterogeneity of lunar magmatic processes [9].

In this study, we return to the global nuclear spectroscopy data set acquired by Lunar Prospector to map the abundance of hydrogen within the Procellarum KREEP terrane (PKT) [10]. The concentration of endogenic hydrogen will likely be near the intrinsic detection limits of the lunar neutron spectroscopy dataset (~10 ppm H). Consequently, our primary objective is to improve the accuracy of our analysis by correcting for artifacts caused by the presence of strong neutron absorbers such as Gd and Sm in KREEP, which can mimic H. Outside the polar regions, the epithermal neutron flux is lowest in KREEP-rich terranes. We will determine whether this observation can be explained by neutron absorption, rather than moderation by hydrogen. Otherwise, an enhancement of hydrogen in association with KREEP might be caused by an endogenic component. A preliminary H map based on a model-guided analysis is presented and interpreted.

Data: Neutron counting maps were determined from data accumulated by Lunar Prospector during ~200 days in a 30-km circular polar mapping orbit [11]. Lunar Prospector's Cd-wrapped ³He tube (HeCd) is sensitive to neutrons in the epithermal energy range

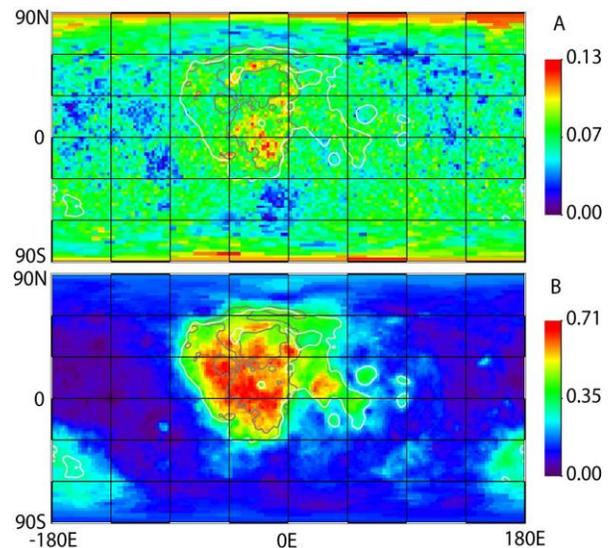


Figure 1. A map of R_{Epi} (A) is compared to R_{HeSn} (B). KREEP-rich regions are enclosed within the grey contour ($Th > 6 \mu\text{g/g}$). Fe-rich mare units are bounded by the white contour ($Fe > 11 \text{ wt.}\%$). The maps are 2° equal area cylindrical projections.

(above about 0.3 eV). A similar Sn-wrapped tube (HeSn) is primarily sensitive to thermal neutrons. The epithermal neutron counting rate is strongly sensitive to hydrogen in the lunar regolith; whereas, thermal neutrons respond strongly to absorption by Fe, Ti, Gd, and Sm [12].

Analysis: For each map pixel, the epithermal counting rate C_{epi} was determined by subtracting a fraction (f) of the counting rate for HeSn (C_{HeSn}) from that of HeCd. Based on modeling, the abundance of hydrogen [H] is proportional to $R_{epi} = \max(C_{epi}) / C_{epi} - 1$, with a constant of proportionality of about 2000 $\mu\text{g/g}$ [1-3]. A map of R_{epi} (Fig. 1A) shows that hydrogen is enhanced at the lunar poles; however, the map also implies that high abundances of hydrogen are also present in KREEP-rich regions. A map of $R_{HeSn} = \max(C_{HeSn}) / C_{HeSn} - 1$ (Fig. 1B), which is to first order sensitive to neutron absorption, shows that neutron-absorbing elements are abundant throughout the Fe-rich mare and KREEP-rich terranes.

A scatter plot of the data (R_{epi} versus R_{HeSn} in Fig. 2) shows that, on average, R_{epi} increases from the highlands into the PKT, implying that the lunar mare are comparatively enriched in hydrogen; however, modeling shows that R_{epi} increases with R_{HeSn} for hydrogen-free lunar sample- and meteorite-compositions (Fig. 2)

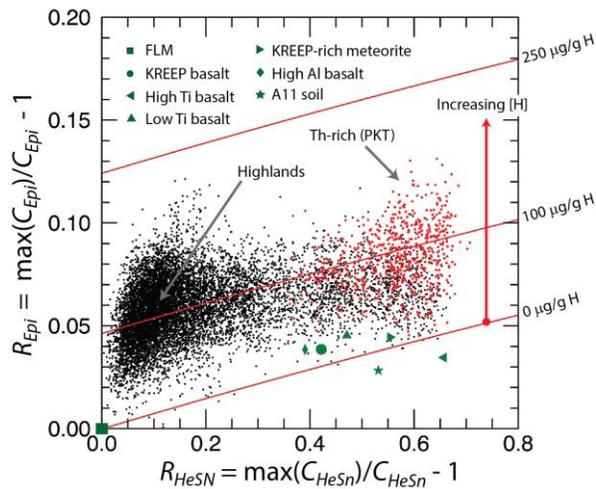


Figure 2. Scatter plot of the epithermal and HeSn counting ratios. The points are map data acquired by Lunar Prospector (Fig. 1). Red points are for KREEP-rich regions ($\text{Th} > 6 \mu\text{g/g}$). Radiation transport model calculations are shown for different lunar materials (symbols). A Feldspathic Lunar Meteorite (FLM) composition [14,15], representative of the lunar highlands, is compared to basalts and KREEP-rich materials. The 0 mg/g H trend line was derived from the data and shifted to 100- and $250\text{-}\mu\text{g/g}$ based on calculations.

due to absorption by Fe, Ti, Gd, and Sm in the epithermal energy range. The lower limit of the data (R_{epi}) is assumed to represent the hydrogen free trend; however, we note that this lower bound, indicated by the red line marked $0 \mu\text{g/g H}$ in Fig. 2, matches the model only for a nontrivial value of f (0.04). This may imply uncertainties in the model or that the PKT is enriched in H on average in comparison to the highlands. The latter might occur if endogenic sources were added to solar wind contributions in the PKT.

The hydrogen-free trend derived from the data was subtracted from the measured R_{epi} values. The residual was multiplied by $2000 \mu\text{g/g}$ to produce a map of hydrogen corrected for absorption (Fig. 3); however, the correction is a first-order approximation. The scatter of the modeled hydrogen-free values about the $0 \mu\text{g/g H}$ trend line (Fig. 2) implies systematic uncertainties $<40 \mu\text{g/g}$ in the resulting map. In addition, modeling indicates that the constant of proportionality between [H] and R_{epi} differs between KREEP-poor and KREEP-rich mare basalts. This is probably caused by strong resonance absorption of low-energy epithermal neutrons by rare earth elements in KREEP. Fe and Ti, which are abundant in basalts, do not have low energy resonances. We expect that improvements in accuracy can be obtained by modeling the hydrogen-free epithermal counting rate and proportionality constant for each map pixel using available compositional data [e.g. 14].

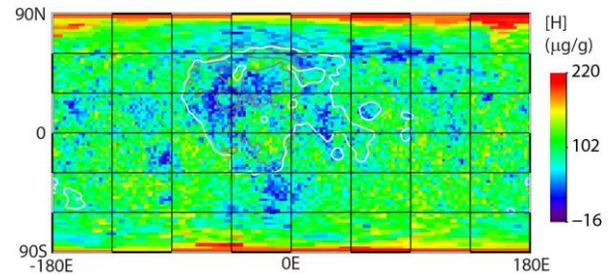


Figure 3. Relative abundance of hydrogen [H], corrected for neutron absorption. KREEP-rich regions are enclosed within the grey contour ($\text{Th} > 6 \text{ ppm}$). Fe-rich mare units are bounded by the white contour ($\text{Fe} > 11 \text{ wt.}\%$). A 2° equal area cylindrical projection is shown.

Conclusion: A potentially strong hydrogen enhancement in KREEP-rich regions (Fig. 1A) is caused, in part, by the absorption of epithermal neutrons by rare earth elements. Once absorption artifacts are removed, the abundance of hydrogen in KREEP-rich regions is still relatively high, similar to highlands regions with elevated concentrations of hydrogen (Figs. 2 and 3). In comparison, the surfaces of adjacent, near-side basins (Procellarum and Imbrium) are hydrogen-poor. While it is likely that the variation of hydrogen within the PKT can be attributed to space weathering, we cannot rule out the possibility that OH-apatite in KREEP contributes to increased hydrogen abundances found in regions with elevated Th. Improved analyses, outlined here, should achieve the intrinsic sensitivity of epithermal neutrons ($\sim 10 \text{ mg/g H}$), which will aid future efforts to detect lunar endogenic hydrogen.

References: [1] Feldman W. C. et al. (1998) *Science*, 281, 1496-1500. [2] Prettyman T. H. et al. (2012) *Science*, 338, 242-246. [3] Lawrence D. J. et al. (2012) *Science*, 339, 292-296. [4] Pieters et al. (2009) *Science*, 326, 568-572. [5] McCord T. B. et al. (2011) *J. Geophys. Res.* 116, E00G05. [6] Lawrence D. J. et al. (2014) this meeting. [7] Klima R. et al. (2013), *Nature Geosci.* 6, 737-741. [8] McCubbin F. M. et al. (2010) *PNAS*, 107, 11223-11228. [9] McCubbin F. M. et al. (2011) *Geochim. Cosmochim. Acta*, 75, 5073-5093. [10] Jolliff, B. L. (2000) *J. Geophys. Res.*, 105, 4197-4216. [11] Maurice S. et al. (2004) *J. Geophys. Res.*, 109, E07S04. [12] Elphic R. C. et al. (2000) *J. Geophys. Res.*, 105(E8), 20333-20345. [13] Lawrence D. J. (2006) *J. Geophys. Res.*, 111, E08001. [14] Prettyman T. H. (2006) *J. Geophys. Res.*, 111, E12007. [15] Korotev, R. L. (2003) *Geochim. Cosmochim. Acta*, 67, 4895 - 4923.