Bulk Hydrogen Abundances in the Lunar Highlands: Measurements from Orbital Neutron Data. David J. Lawrence[1], Sylvestre Maurice[2], Patrick N. Peplowski[1], Thomas H. Prettyman[3], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA (David.J.Lawrence@jhuapl.edu); [2]IRAP, Toulouse, France; [3]Planetary Science Institute, Tucson, AZ, USA.

Introduction: In recent years, our understanding of hydrogen (H), water, and other volatile materials on the Moon has changed dramatically [1]. This new understanding has resulted from: 1) new measurements and analyses of enhanced H concentrations at the lunar poles [e.g., 2,3,4]; 2) new orbital measurements showing exogenic and endogenic enhancements of H_2O/OH in non-polar lunar regions [5,6]; and 3) new sample measurements revealing unexpectedly high amounts of water in lunar samples [7]. Despite these advances, there does not yet exist a large-area, non-polar map of bulk lunar H abundances across the lunar surface. Such a map would be important and useful as a tie point to lunar sample studies as well as for understanding processes that relate to all aspects of global lunar volatiles. Recent data and analyses from the Lunar Reconnaissance Orbiter (LRO) Diviner instrument [8] are providing new understanding of previously collected data from the Lunar Prospector Neutron Spectrometer (LP-NS)[9,10]. This understanding has allowed us to derive a new, map of bulk H concentrations in the lunar highlands.

Global Epithermal Neutron Data: Cosmic ray-generated epithermal neutrons provide a strong measure of planetary H concentrations [11]. A global lunar map of epithermal neutrons derived from LP-NS data (Fig. 1)[9,10] can be divided into three primary regions: 1) polar regions; 2) Procellarum KREEP Terrane (PKT); and 3) Feldspathic Highlands Terrane (FHT). The polar regions show decreases in epithermal neutron count rates that are indicative of enhanced polar H concentrations. These polar data have been extensively studied [e.g., 9-12] and polar maps of footprint-averaged H concentrations have been derived [10,12]. The PKT shows a strong epithermal neutron decrease that is spatially-correlated with Th, Fe, and Ti concentrations. Lawrence et al. [10] argued that the PKT count rate decreases are not primarily related to H concentrations but to neutron absorbers. However, the magnitude of these decreases is not fully understood and it is possible that epithermal neutrons also indicate KREEP-correlated locations of enhanced H [13].

The behavior of epithermal neutrons in the FHT are not fully understood. There is an expectation that epithermal neutrons in this region should be related to the concentrations of solar wind-implanted H. If this is the case, then young craters, which have relatively little exposure to solar wind, should be depleted in H and enhanced in epithermal neutrons. Using an early version of LP-NS data, Johnson et al. [14] showed that surface maturity [15], which is a proxy for surface weathering and hence implanted H, indicated only a moderate correlation with global epithermal neutrons. However, it was suggested that factors in addition to solar wind H, such as nearside enhancements of rare earth elements, might be affecting epithermal neutron variations. Subsequent analyses of LP-NS data [9] and new LRO data from the Diviner instrument have now allowed new understanding to be gained about lunar highlands epithermal neutrons and hence bulk H concentrations in the lunar highlands.

Diviner vs. Epithermal Neutrons: LRO Diviner data have been used to measure a thermal infrared feature called the Christiansen Feature (CF)[8], which provides diagnostic information about silicate mineralogy. The wavelength position of the CF, which occurs between 7 and 9 μm, is highly sensitive to the composition of lunar materials [16,17]. Specifically, for mafic materials rich in Fe and Ti, the CF position is shifted to long wavelengths (>8 μm) and for feldspathic materials, the CF position is shifted to short wavelengths (<8 μm).

A direct comparison between the LP epithermal neutron and Diviner CF datasets shows a clear correlation for FHT-selected regions (Fig. 2). This correlation indicates that epithermal neutrons and the CF are sensitive to similar properties of the lunar surface. Based on the observation that the CF feature is sensitive to the amount of feldspathic versus mafic materials [16] and therefore Fe [18], an initial explanation of the correlation is that the epithermal neutrons in the FHT are inversely correlated with the Diviner CF due to slight variations in neutron absorbing elements such as Fe. However, based on the observed and model-validated epithermal neutron variations in higher Fe regions [10], epithermal neutron variations observed in the FHT would correspond to a >10 wt.% variation in Fe. This large Fe variation is not likely as most all FHT locations have Fe concentrations less than 4 wt.% [19,20].

If the 5% epithermal neutron variation in the FHT is due to changes in H, the neutron variation corresponds to an H concentration range of 0 to 100 ppm H. This range of concentrations is consistent with the H dynamic range measured in lunar samples [21]. Greenhagen et al. [8] and Allen et al. [18] state that the measured CF appears to be unexpectedly sensitive to space weathering effects such that older, weathered surfaces have relatively long wavelength CF values. Surfaces with more space weathering will have relatively more solar wind implanted H. This information is consistent with the idea that FHT epithermal neutrons are primarily sensitive to variations in H.

FHT Map of H Concentrations: The CF versus epithermal neutron comparision provides independent confirmation that FHT epithermal neutrons are primarily sensitive to H variations. Using known calibrations [10], a map of FHT H concentrations has been derived (Fig. 3). This map shows H depletions in locations of younger craters (e.g., Tycho) where there has been little time to accumulate large amounts of solar wind H. In contrast, older regions far away from young impact craters have higher H concentrations. These associations are consistent with the idea that FHT H concentrations are largely due to solar wind implanted H. A few conclusions can be drawn from these results. First, maturity is a bulk soil property that is modified by long term space weathering. As such, it does not represent a surficial (top 10s to 100s microns) property. As a consequence, these bulk hydrogen measurements and surficial OH/H_2O measurements [5] are not measuring the same quantity. However, isolated, small scale (<50 km) surficial enhancements are not ruled out by this analysis [22]. In addition, since epithermal neutrons are mostly sensitive to bulk and not surficial H, it is unlikely that neutrons are sensitive to local time variations of surficial hydrogen [23] as suggested by recent studies [24].

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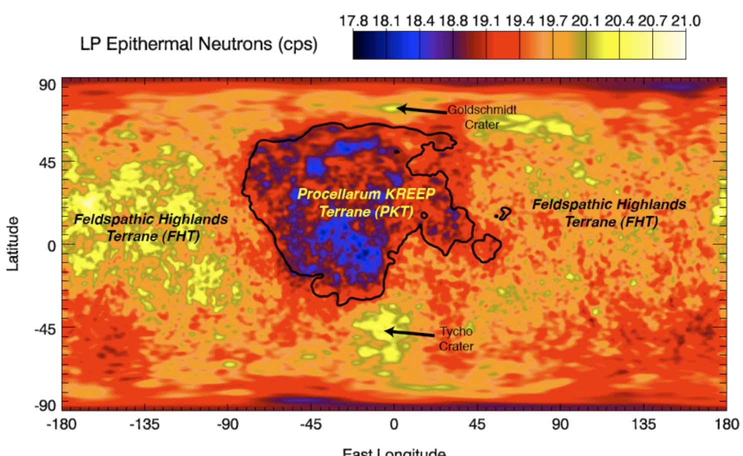

Fig. 1. Global lunar map of epithermal neutrons measured with the LP-NS [9,10].

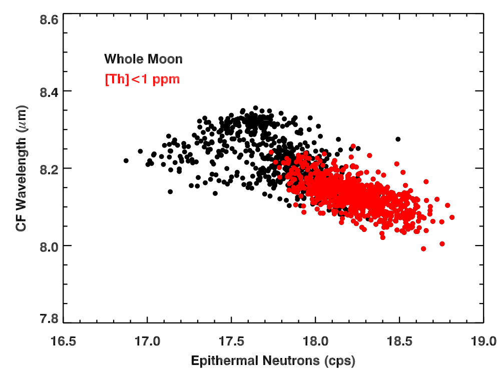

Fig. 2. Epithermal neutrons versus CF wavelength [8] for the whole Moon (black) and low-Th regions (red). The low-Th regions shows a clear correlation between the two values.

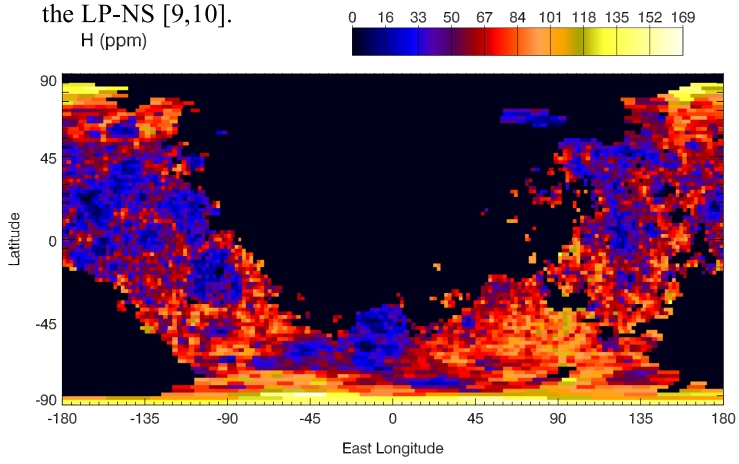

Fig. 3. Map of H concentrations in the lunar highlands for low-Th regions [Th<1 ppm] in units of ppm.