The Local-time variations of Lunar Prospector epithermal-neutron data

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Abstract

We assess local-time variations of epithermal-neutron count rates measured by the Lunar Prospector Neutron Spectrometer. We investigate the nature of these variations and find no evidence to support the idea that such variations are caused by diurnal variations of hydrogen concentration across the lunar surface. Rather we find an anticorrelation between instrumental temperature and epithermal-neutron count rate. We have also found that the measured counts are dependent on the temperatures of the top decimeters of the lunar subsurface as constrained by the Lunar Reconnaissance Orbiter Diviner Lunar Radiometer Experiment temperature measurements. Finally, we have made the first measurement of the effective leakage depth for epithermal-neutrons of \textasciitilde{}20 cm.

Keywords: the Moon; Hydrogen; Surfaces, planets; Neutron Spectroscopy

1. Introduction

The mapping of hydrogen on the near surface of the Moon has been one of the focal points of the exploration of the Moon. Neutron spectroscopy has been central to this endeavor and allows one to probe the top few decimeters (e.g. Feldman et al., 1998; Lawrence et al., 2006). Neutron spectrometers detect leakage neutrons resulting from the interaction of galactic cosmic rays (GCR) and the chemical elements present in the top layers of the planetary subsurface. These neutrons lose energy by interacting with the surrounding lunar material, and different elastic and inelastic scattering cross-sections produce different amounts of moderation and capture. Since the Moon has no atmosphere, cosmic rays reach the surface without being absorbed. Neutrons can leak from the near subsurface without being scattered further or absorbed. In addition, the Moon has no atmosphere, cosmic rays reach the surface without being absorbed. Neutrons can leak from the near subsurface without being scattered further or absorbed. In addition, the Moon has a characteristic composition pattern (dichotomy between Fe and Ti-rich maria and Al-rich highlands), to which neutron measurements are highly sensitive. Finally, from returned samples, the lunar regolith is recognized to be hydrogen poor at equatorial latitudes (<100 ppm, Heiken et al., 1991). This \textit{a priori} information has played a major role in the interpretation and understanding of the orbital neutron data.

According to their kinetic energy, $E_{\text{kin}}$, neutrons are typically divided into three different energy bands: fast, epithermal and thermal. These correspond to $E_{\text{kin}} > 0.5$ MeV, $0.4 < E_{\text{kin}} < 0.5$ MeV and $E_{\text{kin}} \leq 0.4$ eV respectively. Briefly, thermal neutrons are particularly sensitive to Fe, Ti, Gd and Sm in the absence of $H$ (Elphic et al., 1998, 2000). Epithermal-neutrons are strongly moderated by $H$ (Feldman et al., 1993) and therefore provide a robust measure of $H$ concentrations and their spatial variations. Multiple studies have reported the presence and concentrations of $H$ enhancements at the lunar poles (Feldman et al., 1998; Eke et al., 2009; Teodoro et al., 2010, 2014) as well as $H$ concentrations within non-polar regions (Lawrence et al., 2015).

In this article we study the daily variations of epithermal-neutron count rates from the Lunar Prospector neutron spectrometer (LPNS) to inquire if such potential variations are sensitive to daily variations in $H$ concentrations. This study is prompted, in part, by a report of time-variable concentrations of surficial (top tens of micrometers) $H_2O/OH$ that have been observed with spectral reflectance data (Sunshine et al., 2009). If such time variable $H$ concentrations extend to macroscopic depths of multiple mm to cm (Lawrence et al., 2011), then such variations could in principle be observed with orbital neutron data. Preliminary analysis of data from the Lunar Exploration Neutron Detector (LEND) on the NASA Lunar Reconnaissance Orbiter (LRO) mission has shown a diurnal count rate variation, which has been interpreted as daily variations in $H$ concentrations (Livengood et al., 2014). Such findings, if confirmed, could lead to important consequences to our understanding of the hydrogen distribution at the lunar surface. Here, we will show that LPNS epithermal-neutron count rates also show variations with solar local time, but that these variations are anti-correlated with variations in instrumental temperature. Furthermore, the LPNS daily variations show a dependence on the temperatures at the top few decimeters of the lunar subsurface as predicted by the numerical work of Little et al. (2003) and Lawrence et al. (2006). These findings suggest that rather than reflecting diurnal changes in the hydrogen content of the lunar regolith, the temporal fluctuations in the count rates are due to small residual systematic effects in the data reduction.

In Section 2 we present the datasets used throughout the article while in Section 3 we perform the analysis of the epithermal dataset. We finish the article in Section 4 with our conclusions and discussion.
2. Datasets

In this section we will briefly detail the main characteristics of the epithermal-neutron dataset gathered by the LPNS, which is in the public domain at the Planetary Data System (PDS) (http://pds-geosciences.wustl.edu/missions/lunarp/). We will also use temperature measurements of the lunar surface collected by the Diviner Lunar Radiometer on Lunar Reconnaissance Orbiter. These measurements are also available at PDS (http://pds-geosciences.wustl.edu/missions/lro/diviner.htm).

2.1. LPNS Counting data

The Lunar Prospector Neutron Spectrometer, designed and built at the Los Alamos National Laboratory, consists of two gas proportional counters containing helium-3. The neutrons that are captured by helium-3 nuclei within the detectors produce a unique energy signature that is then detected and counted. The two sensors have different covers: one is covered in cadmium, the other in tin. The cadmium cover screens out thermal neutrons while the tin counterpart does not. Differences in the counts between the two tubes thus quantify the detected number of thermal neutrons. The neutron spectrometer was located at the end of a 2.5 m boom, thus reducing the background from the main body of the spacecraft. For further details regarding the neutron spectrometer see Feldman et al. (2004).

The epithermal-neutron counting rate and spacecraft altitude time series are shown in Figure 1, along with other parameters (neutron sensor temperature and pulse height peak-channel position) used in this study. All data shown in Figure 1 are coloured based on the different mission phases described in Table 2 of Maurice et al. (2004). Green shows data from the High 1 phase (average altitude \(\sim 100\) km), cyan shows data from the High 2 phase (average altitude \(\sim 100\) km, flipped spacecraft spin axis), magenta shows data from the Low 1 phase (average altitude \(\sim 40\) km), and violet shows data from the Low 2 phase (average altitude \(\sim 30\) km). The origin of time was set at 1st of January 1998.

Hereafter we will use data within the latitude range \([-55^\circ, 55^\circ]\), coming either from the High 1 (hereafter High Altitude) or Low 2 (hereafter, Low-altitude) phases, respectively. A third dataset with all the measurements within the same latitude range will be termed Overall. The number of \(8s\) measurements within Overall, High altitude and Low-altitude datasets are 2,851,632, 1,324,569 and 939,668, respectively. With this choice of latitudes we are considering those parts of the lunar surface whose epithermal signal is not dominated by the hydrogen enhancements in the top few decimeters of regolith. The individual count rates were normalized to altitude 30 km (Maurice et al., 2004).

2.2. Lunar Prospector Instrumental Temperature and Energy spectrum information

The LPNS included a temperature sensor. Its time-series variation is presented in panel c) of Figure 1. As with the count rate data we will use data within [latitude] < \(55^\circ\). The LPNS returned pulse height spectra of the \(^3\)He neutron captures, and a key feature is the 764 keV full-energy capture peak (see Figure 5). Panel d) of Figure 1 shows the Cd \(^3\)He sensor peak-channel position versus time. The large jump in peak-channel position around time \(\sim 300\) days coincides with an increase in the detector’s high voltage.

2.3. Diviner/LRO temperature diurnal variation data

The Diviner Lunar Radar Experiment on board LRO is an imaging multi-channel solar reflectance and infrared radiometer. This instrument maps the temperature of the lunar surface at < 500 meter horizontal scales. Diviner data sets are produced by the Diviner Science Team at the University of California, Los Angeles. Here we use temperature information as function of the lunar local time at different depths of the lunar subsurface. We will employ the Diviner measurements and model predictions constrained by such measurements (see Siegler et al., 2011) for
details). Upper left panel in Figure 2 shows the Diviner measurements and the remaining eight panels show the model’s predictions at depths of 1, 2, 3, 4, 5, 10, 20 and 30 cm.

As expected, subsurface temperatures have a strong dependence on the local time, depth and latitude. At the surface, temperature peaks at the local midday. At deeper depths, the temperature maximum shifts towards later times of the day, as expected for a diurnal temperature wave.

3. Analysis

To quantify the variability of the epithermal count rate, \(cr(x, t)\), we introduce the stochastic overcount rate variable, \(\delta cr\):

\[
\delta cr(x, t) \equiv \frac{cr(x, t) - cr_f(x)}{cr_f(x)} = \frac{cr(x, t)}{cr_f(x)} - 1, \tag{1}
\]

where \(cr_f(x)\) is the fiducial count rate map at a given local time instant. Thus, the overcount rate field quantifies the change in counting rate, \(cr(x, t) - cr_f(x)\), relative to a fiducial state, \(cr_f(x)\). Hereafter, we will present results obtained using a fiducial state defined as the mean epithermal counting rate in a two-hour bin centered around 6 pm = +90 degrees from the sub-solar longitude on the Moon. Figure 3 presents the fiducial count rate maps for the overall, high-altitude and low-altitude datasets. \(cr(x, t)\) and \(cr_f(x)\) are pixellated in \(5^\circ \times 5^\circ\) bins: \(cr(x_{ij}, t_k)\) and \(cr_f(x_{ij})\), where the spatial coordinate \(x\) is partitioned in latitude \(i \in \{1, \cdots, 36\}\) and longitude \(j \in \{1, \cdots, 72\}\), while the two-hour local time bins are represented by \(k \in \{1, \cdots, 12\}\). In Figure 4 we present the averaged overcount rate, \(\langle \delta cr(x_{ij}, t_k) \rangle_{ij}\), in two-hour local time bins centered around \(t_k\)

\[
\langle \delta cr(x_{ij}, t_k) \rangle_{ij} \equiv \frac{1}{n_{pixels}(t_k)} \sum_{ij} \delta cr(x_{ij}, t_k) W(x_{ij}), \tag{2}
\]

where \(\langle \cdots \rangle_{ij}\) denotes the average over all the pixels at a given instant \(t_k\), the sum is over all the spatial pixels \((i, j)\), \(W(x_{ij})\) is a spatial “mask” applied to the data as the means to exclude the polar regions:

\[
W(x_{ij}) = \begin{cases} 
1, & \text{at latitudes } [-55^\circ, 55^\circ], \\
0, & \text{everywhere else,}
\end{cases} \tag{3}
\]
show significant peak-to-peak variations, \( \sim 3 \) the random errors are smaller than \( c \) magnitude.

In principle, these epithermal-neutron local-time variations may be due to variations in bulk hydrogen concentrations across the lunar surface, which is an idea suggested by Livengood et al. (2014) to explain similar variations in LRO/LEND data. However, a comparison of LPNS and LEND data argue against such an interpretation. Specifically, even though the magnitude of the LPNS and LEND local-time variations are similar (2.7% for LPNS versus 2% for LEND), their qualitative behavior is fundamentally different. The LEND data show a single maxima (6 local time [LT]) and minima (15 LT), whereas the LPNS data show two maxima (7 LT and 15 LT) and minima (12 LT and 24 LT). If there were true local-time hydrogen variations that caused a 2 to 2.7% variation in epithermal-neutron count rates, the measured local-time behavior should be similar in both datasets. The fact that their local-time behavior is different suggests that other non-hydrogen systematic variations may be responsible for the observed local-time variations. Because the two sets of measurements were made with different instruments on different spacecraft, such non-hydrogen variations need not be identical in both datasets. Here, we investigate possible sources of non-hydrogen systematic variations in the LPNS data. If we can show that such systematic effects can account for all or most of the local-time variations, then we can conclude that varying hydrogen concentrations are not the cause of these variations. Below, we discuss two such systematic effects: variations in LPNS sensor temperature and variations in lunar surface and subsurface temperatures.

\[ n_{\text{pixels}}(l_i) \equiv \sum_{l_j} W(x_{ij}). \]  

The three derived time series (overall, high and low-altitude) show significant peak-to-peak variations, \( \sim 0.0273 \), given that the random errors are smaller than \( 3.0 \times 10^{-4} \).

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![Figure 3: Fiducial states adopted in this article. a) Overall data. b) High Altitude. c) Low-Altitude. The data is pixelized in 5\textdegree \times 5\textdegree bins.](image)

3.1. Epithermal-neutron count rate dependence on LPNS sensor temperature

We first investigate if there is evidence that LPNS sensor temperatures might be related to systematic variations in the epithermal-neutron count rate that have not yet been removed in the prior data reduction procedures (Maurice et al., 2004). Specifically, we examine if the varying sensor temperatures are related to gain variations (or a multiplicative shift) in the neutron sensor pulse height spectra. If such gain variations exist, then we ask if such variations are related to the 2.7% count rate variations. We note that the variations in the high and low-altitude data are qualitatively similar, so unless otherwise noted, we hereafter only carry out analyses for the low-altitude LPNS data.

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![Figure 4: Upper panel Average overcount rate per local time bin. The fiducial map is the mean counting rate at a given location over all the time series. The random errors in the measurements are smaller than \( 3.4 \times 10^{-4} \), 5.2 \times 10^{-4}, 3.5 \times 10^{-4}, 3.4 \times 10^{-4} \) for the overall (black), high altitude (green) and low-altitude (violet) data, respectively. Lower panel Average NS temperature per local time bin. The random errors in the measurements are smaller than \( 3.4 \times 10^{-4} \), 8.2 \times 10^{-4}, 5.2 \times 10^{-4}, 5.2 \times 10^{-4} \) for the overall (black), high altitude (green) and low-altitude (violet) data, respectively. The shaded regions of the diagrams represent the night-side. The x-axis tickmarks coincide with the local time bin centers.](image)
nels used by Maurice et al. (2004) for the count rate change measurements), there is a 0.7% counting rate change. While this count rate change is smaller than the measured change, it is in the same direction as the measured data, such that lower gain data (which corresponds to lower instrument temperature) shows a larger counting rate, and therefore demonstrates that a varying gain caused by a varying temperature can result in varying LPNS epithermal-neutron count rates.

3.2. Neutron Spectrometer sensor temperature correction

To remove the sensor temperature induced count rate variation, we have implemented the following two-step procedure: i) find the linear correlation coefficient between low-altitude time-series count rates and their associated sensor temperatures, and ii) use the linear relationship between those two variables to “de-trend” the data. A least squares fit to the data produces

\[
cr = -0.0194 \cdot T_{\text{sensor}} + 19.170,
\]

where the sensor temperature, \( T_{\text{sensor}} \), is expressed in °C and the measured count rate, \( cr \), in \( s^{-1} \). This relationship is applied to produce the sensor temperature-corrected count rates,

\[
cr' \equiv cr + 0.0194 \cdot (T_{\text{sensor}} - \bar{T}_{\text{sensor}}),
\]

where \( \bar{T}_{\text{sensor}} \) denotes the mean sensor temperature. These corrected count rates lead to fluctuations in the low-altitude over-count rates that are reduced from 2.73% to 1.60%, as shown in Table 3 and the violet line in the upper panel of Figure 6. In the same panel of Figure 6 we also present the uncorrected data (green).

3.3. Count rate correlation with lunar surface and subsurface temperature

Little et al. (2003) and Lawrence et al. (2006) used the Monte Carlo transport code MCNPX to study the transport of neutrons in typical lunar soils and found that thermal and epithermal count rates are dependent on soil temperature. Here, we consider a variety of subsurface temperatures as functions of both latitude and local time, constrained by Diviner measurements (Siegler et al., 2011).

To take into account the effects of the lunar subsurface temperature we consider an “average soil” made up of equal fractions of FAN, Luna 20 (L20), Luna 24 (L24), Apollo 11 (A11) and Apollo 12 (A12). In panel a) of Figure 7 we reproduce
parameters were obtained using a linear least squares fit to the points in panel a) of Figure 7. For further details regarding these soils see Lawrence et al. (2006).

Table 1: Various soil parameters, \((a_{\text{soil}}, b_{\text{soil}})\), considered in this work. These parameters were obtained using a linear least squares fit to the points in panel a) of Figure 7. For further details regarding these soils see Lawrence et al. (2006).

| Soil type      | \(a_{\text{soil}}\) | \(b_{\text{soil}}\) |
|---------------|-----------------|-----------------|
| FAN 20 (L20)  | 20.80           | 0.00280         |
| Lunar 11 (A11)| 20.40           | 0.00160         |
| Apollo 12 (A12)| 20.08           | 0.00211         |
| Lunar 24 (L24)| 19.97           | 0.00163         |

Table 2: Equation 8 linear least squares fit parameters, \((a'_{\text{depth}}, b'_{\text{depth}})\), at the various depths used to model the epithermal count rates versus soil temperature.

| Depth | \(a'_{\text{depth}}\) | \(b'_{\text{depth}}\) |
|-------|-----------------|-----------------|
| 0 cm  | 19.46           | 0.00036         |
| 1 cm  | 19.38           | 0.00067         |
| 2 cm  | 19.19           | 0.00143         |
| 3 cm  | 18.98           | 0.00227         |
| 4 cm  | 18.98           | 0.00227         |
| 5 cm  | 18.84           | 0.00284         |
| 10 cm | 18.88           | 0.00266         |
| 20 cm | 19.67           | -0.00056        |
| 30 cm | 19.46           | 0.00036         |

To match the “average lunar soil” count rate versus soil temperature predictions shown at the upper panel of Figure 7 and the LPNS-Diviner measurements of the same relationship shown at the lower panel of the same figure we introduce the following transform:

\[
cr_{\text{soil,depth}} = cr_{\text{depth}} + \left( a_{\text{soil}} - a'_{\text{depth}} \right) + T_{\text{soil,depth}} \left( b'_{\text{depth}} - b_{\text{soil}} \right) + \left( b_{\text{soil}} - b'_{\text{depth}} \right) \left( T_{\text{soil,depth}} - T_{\text{soil,depth}} \right) . \tag{9}\]

Here, \(T_{\text{soil,depth}}\) is the average soil temperature at a given depth.

Briefly, the transform is made up of two parts: \(i\) move the measured point linear upwards in such a way that makes it coincide with the value of the model predictions at \(T_{\text{soil,depth}}\) (second and third terms of the rhs in the above equation), and \(ii\) make the slope of the linear fit to the measured points match the model counterpart, which is denoted by the last term in Equation 9.

In the upper panel of Figure 6 we show the average overcount rate, \(\langle \text{octr} \rangle\), corrected for sensor temperature and subsurface temperature effects (black). In the lower panel of the same figure we show the overcount rate as corrected for subsurface temperatures at different depths. Table 3 contains the peak-to-peak variation of the overcount rate for different subsurface temperature corrections, with the minimum variation occurring for the subsurface depth of 20 cm. This result shows that if we correct the LPNS epithermal-neutron count rates for temperature at an effective depth of 20 cm, we can minimize the local-time variations. Because the remaining variation is quite small (<0.5%), we therefore find that there is no need to invoke local-time varying hydrogen concentrations to explain most of the LPNS local-time epithermal-neutron variations. We further note that Little et al. (2003) predicted that the “effective” depth for thermal-neutron emission is 30 g/cm², which for a soil density of 1.5 g/cm², results in a physical depth of 20 cm. This is the same value as our data-constrained effective depth for epithermal-neutrons, and supports the interpretation that much of the measured local-time neutron variations are caused by subsurface temperature variations.

4. Discussion and Conclusions

In the prior section, we have shown that the LPNS epithermal-neutron count rate data equatorward of 55° show a local-time variation that has a magnitude of 2.7%. We have found that corrections for varying LPNS sensor temperatures and lunar subsurface temperatures can reduce this 2.7% variation to less than 0.5%. Livengood et al. (2014) have also found ~2% local-time variations in the LEND epithermal-neutron count rates. Their interpretation of this result was that these variations were cause by mobile hydrogen that deposits once the sun sets, since the surficial temperature is low enough to lead to a long residence time during the night. It then leaves the lunar surface at dawn as higher temperatures imply very short residence times (see Schorghofer and Taylor 2007) for a definition of residence time and dependence on temperature). Because we can quantitatively account for all but 0.5% of the LPNS local-time variation, we find little-to-no support for the interpretation that varying hydrogen concentrations are the dominant cause of the local-time epithermal-neutron variations in either the LPNS or LEND datasets.

Even though the remaining LPNS local-time variations do not exhibit the time dependence expected for diurnal variations suggested by Livengood et al. (2014), we can nevertheless investigate the implications if the remaining 0.5% local-time variations are due to time-variable hydrogen concentrations. Specifically, if a 0.5% diurnal change in epithermal-neutron counting
Figure 7: Panel a) This panel, as in Lawrence et al. (2006), shows count rates versus surface temperatures. Each color denotes a different soil: FAN (brown), Lunar 20 (L20, powder green), Apollo 11 (A11, orange), Apollo (A12, violet) and Lunar 24 (L24, blue navy). The dashed black line denotes the “average lunar soil”. Panel b) The measured count rates versus surface and sub-surface temperature. Dotted lines represent the box-smoothed count rates. Solid lines denote the least squares fits to the smoothed data. For clarity the 5, 10 and 20 cm curves are shifted upwards by 0.25, 0.50 and 0.75 s−1.

| Depth         | (δcr)min | (δcr)max | Δcr  |
|---------------|----------|----------|------|
| Overall       | -0.0160  | 0.0075   | 0.0235 |
| High altitude | -0.0134  | 0.0091   | 0.0226 |
| Low-altitude  | -0.0144  | 0.0130   | 0.0273 |

Low-altitude sensor temperature corrected: -0.0075 0.0075 0.0150

Table 3: Peak-to-peak variation of the LPNS overcount rate variation, Δcr = (δcr)min − (δcr)max, of the different datasets applied in this article.

In summary, we have shown that the LPNS epithermal-neutron data do exhibit local-time variations that have a magnitude of 0.27%. However, these variations can be understood as being due to systematic variations of the LPNS sensor temperature as well as lunar subsurface temperatures. An additional result of this work is that by showing the LPNS local-time variations can be minimized by a subsurface temperature at a depth of 20 cm, the LP neutron data have shown to be consistent with modeled subsurface temperatures, neutron-transport modeled temperature dependencies, as well as the predicted effective depth of subsurface neutron emission.

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