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The variations of neutron component of lunar radiation background from LEND/LRO observations

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ABSTRACT

Lunar neutron flux data measured by the Lunar Exploration Neutron Detector (LEND) onboard NASA's Lunar Reconnaissance Orbiter (LRO) were analyzed for the period 2009–2014. We have re-evaluated the instrument's collimation capability and re-estimated the neutron counting rate measured in the Field of View (FOV) of the LEND collimated detectors, and found it to be 1.0 ± 0.1 counts per second. We derived the spectral density of the neutron flux for various lunar regions using our comprehensive numerical model of orbital measurements. This model takes into account the location of the LEND instrument onboard LRO to calculate the surface leakage neutron flux and its propagation to the instrument detectors. Based on this we have determined the lunar neutron flux at the surface to be $\sim$2 neutrons/[cm^2 sec] in the epithermal energy range, 0.4 eV to 1 keV. We have also found variations of the lunar neutron leakage flux with amplitude as large as a factor of two, by using multi-year observations to explore variations in the Galactic Cosmic Ray (GCR) flux during the 23rd–24th solar cycles.

1. Introduction

NASA's Lunar Reconnaissance Orbiter (LRO) has been in orbit around the Moon since July 2009 and has been confirmed for a second mission extension through September 2016. The purpose of the LRO mission is to provide a high-quality legacy data set to guide lunar exploration for decades to come, including information on cartography, topography, geology, geophysics, geochemistry, and the space environment (Chin et al., 2007; Vondrak et al., 2010). Evaluating the distribution and quantity of volatiles, in particular, the near-surface availability of water or other hydrogen-bearing species is an essential geochemical task important to astrobiology investigations and future in situ resource utilization (ISRU). The Lunar Exploration Neutron Detector (LEND) instrument is essential to this task (Mitrofanov et al., 2008, 2010a). LEND was designed to measure both omnidirectional neutron flux in different energy ranges and epithermal neutrons with a collimated Field of View (FOV; see Chin et al., 2007; Vondrak et al., 2010). The LEND collimator provides observations of the footprint under the instrument with a radius of 5 km at an altitude of 50 km (Mitrofanov et al., 2008, 2010a; Litvak et al., 2012a, 2012b).

Neutron remote sensing enables the detection of hydrogen-bearing volatiles within the upper $\sim$1 m of planetary regolith, probing beneath the surface without digging and investigating unilluminated regions. In 1998, the Lunar Prospector (LP) mission's Neutron Spectrometer (LPNS) discovered evidence for hydrogen in the Moon's polar regolith (Feldman et al., 1998, 2000; Lawrence et al., 2006). LEND is designed to expand on this discovery by evaluating the degree to which hydrogen may be isolated within permanently shadowed regions (PSRs) near the poles, versus its broad distribution within the generally cold polar regolith (Mitrofanov et al., 2010b, 2012; Sanin et al., 2012).

Galactic Cosmic Rays (GCR) strike the lunar surface and produce high-energy neutrons through spallation reactions with the primary nuclei in the lunar regolith. Fast neutrons propagate in the lunar subsurface and interact with soil nuclei losing energy from neutron inelastic scattering and capture processes that produce characteristic gamma-ray lines. The energy spectrum of the

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resultant neutron leakage flux observed from lunar orbit is broad. The spectrum begins with a Maxwellian distribution of thermal neutrons (<1 eV), followed by a power law decrease in number density in the epithermal and high-energy epithermal ranges (up to 100 keV) and a saw-tooth shape in the high energy range ($>$ 1 MeV), due to various threshold reactions, terminating with a sharp decrease in the high-energy spallation neutron tail. The neutron leakage spectrum and the outgoing gamma-ray line spectrum provide important physical characteristics about bulk elemental composition, lunar regolith properties and environment, key lunar evolution processes, the short-term and long-term modulation of GCR flux in the heliosphere, and observations of solar activity and solar cycle. Regional variations of neutron flux result from diversity in the elemental composition of the lunar subsurface.

The measured lunar neutron flux has been used in many space studies to evaluate the distribution of particular chemical elements (Feldman et al., 1998, 2000; Lawrence et al., 2002, 2006; Mitrofanov et al., 2012; Litvak et al., 2012a, 2012b). For example, analyses of the variations of in the epithermal neutron flux are used to search for hydrogen and water-ice rich areas on the Moon, because hydrogen is a very efficient moderator of high-energy neutrons (Feldman et al., 1998; Lawrence et al., 2006; Mitrofanov et al., 2011, 2012; Sanin et al., 2012). The presence of major elements like iron and titanium, and trace elements like gadolinium, are distinguishable by the reduction of the neutron flux in the thermal energy range, because these elements have large cross sections to absorb thermal neutrons. The enhancement of elements with high mass numbers such as iron, titanium and aluminum, increases the average atomic mass of the lunar soil and the production of fast neutrons in the high energy part of the neutron leakage spectrum (Maurice et al., 2000; Lawrence et al., 2006; Litvak et al., 2012a, 2012b).

Episodic strong solar flares, solar particle events, and long-term variations of the GCR flux within the solar cycle, can induce time variations in the lunar neutron flux. Thus, neutron flux variations may indicate a variety of processes in the heliosphere, which can enhance the study of distinguishable features and characteristics of the solar cycle. Finally, neutrons deposit a significant part of the total radiation dose to space materials, which is important to estimate and consider for current and future manned space flight.

This paper includes a short overview of instrument LEND capabilities in Section 2; detailed information about the instrument and data processing procedures can be also found in Litvak et al., 2012a, 2012b. We present updates of the data processing and numerical procedures related to evaluating the lunar neutron signal in the FOV of the LEND collimated detectors (Sections 3 and 4). Sections 5–7 are devoted to evaluating the neutron leakage spectra for different lunar compositions and analyzing long-term variations of the lunar neutron flux due to variations of GCRs.

2. Instrument description

LEND consists of nine neutron sensors that detect neutrons in several energy bands (Litvak et al., 2012b), see Fig. 1. Eight detectors are identical proportional counters, filled with 20 atm of ^{3}He gas. Each sensor's detection efficiency is nearly 100% in the low energy range and decreases by a factor of 10 at $\sim$500 eV (see Fig. 2 in Litvak et al., 2012b). These sensors detect thermal and epithermal neutron flux. Four of these eight detectors are collimated sensors of epithermal neutrons (CSETN1-4) installed inside a neutron collimator composed of polyethylene and ^{10}B layers. The collimator absorbs thermal and epithermal neutrons that would otherwise impinge on the CSETN detectors at large off-nadir angles, 14–75; the acceptance angle for the lunar neutron flux is $<14°$ from nadir direction (see Fig. 3 and the discussion in Section 4). The top of each collimated counter is nadir-pointing and covered by a 0.5 mm thick Cd filter to capture neutrons with energies <0.4 eV prior to reaching the detector. Thus, the

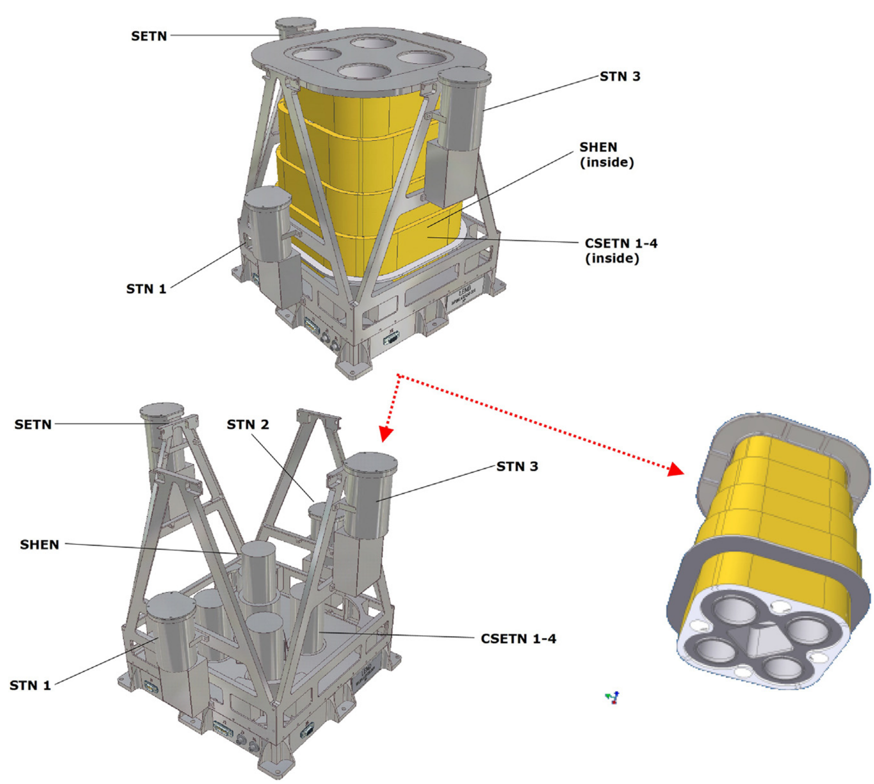

Fig. 1. Instrument LEND has a set of nine thermal and epithermal sensors, fast neutron sensor, and a collimation module.