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Operation of a ^{3}He proportional counter in the Ganymede radiation environment

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ABSTRACT

Neutron spectroscopy has the potential to address many of the scientific objectives of the Jupiter Ganymede Orbiter mission. The most significant challenge is understanding the response of a neutron spectrometer to the intense radiation environment around Ganymede. This study uses data from the Lunar Prospector Neutron Spectrometer to benchmark simulations of the performance of a similar instrument in Ganymede orbit. A solar particle event observed by the Lunar Prospector Neutron Spectrometer serves as a surrogate for the charged particle environment around Ganymede, facilitating a study of the instrument response using data acquired in an environment very similar to the radiation environment found at Ganymede. Based on the conclusions of this study, modifications to a Lunar Prospector-style neutron spectrometer are suggested to allow for the operation of such an instrument in Ganymede orbit. Simulations of the expected signal, based on current models of the surface composition, show this instrument would be capable of compositionally characterizing the nature and extent of surface ice deposits.

1. Introduction

1.1. Neutron Spectroscopy at Ganymede

Neutron spectroscopy has proven to be an excellent tool for the remote characterization of the surface composition of planets with little or no atmosphere. This is accomplished by measuring the neutron flux emanating from a planetary surface. This neutron flux is the result of interactions between high-energy protons, which are the dominant component of galactic cosmic rays, and the surface. These interactions result in the production of spallation neutrons, which subsequently interact with the surface though processes such as elastic scattering, inelastic scattering, and neutron radiative capture (Prettyman, 2006) until they either lose all of their energy in the surface or escape into space. The magnitude and shape of the escaping neutron flux contain compositional information about the surface, including the abundance of neutron absorbing elements, for example Fe and Ti, and neutron moderators such as hydrogen. The sensitivity of neutron measurements to hydrogen has made neutron spectroscopy a vital tool for the detection of water deposits on the surfaces of other worlds, where neutron measurements have successfully identified enhanced hydrogen in the polar regions of the Moon (e.g. Feldman et al., 1998) as well as quantitatively measured hydrogen abundances on the surface of Mars (e.g. Feldman et al., 2002). Missions are currently underway to make similar measurements on Mercury (Goldsten et al., 2007) and the asteroids 4 Vesta and 1 Ceres (Prettyman et al., 2003).

Future applications of neutron spectroscopy include studying the surface composition of the moons in the outer solar system. An especially promising target is Ganymede, the largest moon of Jupiter. A mission to study Ganymede, the Jupiter Ganymede Orbiter (JGO), is currently under consideration by the European Space Agency. Current mission plans have the JGO spending 180 days in a circular polar orbit around Ganymede at an altitude of 400 km, an ideal orbit for mapping the surface composition using neutron spectroscopy. Such measurements have the capability to compositionally characterize the horizontal and possibly near-surface vertical distribution of water abundance of Ganymede's surface, a primary mission objective for the JGO. In regions with low hydrogen content, neutron spectroscopy is sensitive to composition to depths on the order of 10's of centimeters. Increased water content, as is expected on Ganymede, will reduce the regional depth sensitivity to as low as a centimeter. This contrasts with other remote sensing techniques, which are sensitive to composition to depths of less than 100 μm.

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A significant issue to overcome before neutron spectroscopy can be proposed for the JGO is demonstrating the viability of making neutron measurements in the intense charged particle radiation environment around Ganymede. This radiation takes the form of high-energy charged particles trapped in the Jovian magnetic field. These charged particles, specifically high energy electrons and protons, can induce background signals in the detector that have the potential to obscure the neutron signal. In order to demonstrate the feasibility of making neutron spectroscopy measurements in orbit around Ganymede, studies of charged particle induced backgrounds using existing data from the Lunar Prospector Neutron Spectrometer have been carried out, with the results extended to the Ganymede radiation environment. Using these results, a simulated map of surface water ice units as measured with a neutron spectrometer, based on identified geologic units on Ganymede and assumptions regarding their water abundances, is presented to show the capabilities of this measurement technique.

1.2. *Lunar Prospector Neutron Spectrometer*

A common type of neutron spectrometer is the ^{3}He proportional counter. These instruments have an extensive spaceflight heritage, are exceptionally reliable, and are inherently radiation tolerant. The neutron spectrometer aboard the Lunar Prospector (LP) is used here as a baseline for the study of the behavior of ^{3}He proportional counters around Ganymede.

Lunar Prospector was a NASA Discovery-class mission that operated in lunar orbit from January 12, 1998 to July 31, 1999. One of the objectives of LP was to search for water ice deposits within the permanently shadowed craters of the lunar poles. For this reason the spacecraft carried two ^{3}He proportional counters capable of detecting changes in the lunar epithermal neutron flux, a signature which is highly sensitive to the presence of hydrogen. ^{3}He proportional counters make excellent neutron detectors due to the high cross section for the neutron capture reaction

$$^{3}\mathrm{He}+n\rightarrow p+t \tag{1}$$

The *Q*-value for this reaction is 764 keV, energy that is contained entirely within the kinetic energy of the reaction products, the proton (E_p=573 keV) and triton (E_t=191 keV), and is independent of the incident neutron energy. When both reaction products are stopped within the active volume of the detector the result is a peak at 764 keV, a clear signal for the detection of a neutron as illustrated in Fig. 1.

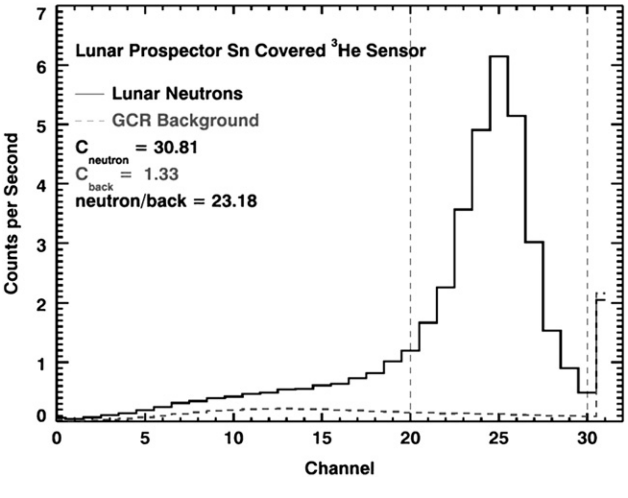

Fig. 1. A typical Lunar Prospector neutron spectrum from the 100 km altitude lunar mapping phase of the mission, with the lunar neutrons and GCR induced background components labeled. The *x*-axis, here shown in channels, covers the range of 0–1 MeV. Note the excellent signal-to-noise (20:1) for the 764-keV neutron capture.

The LP NS consisted of two identical ^{3}He proportional counter neutron detectors located on the end of a boom 2.5 m away from the spacecraft bus (Feldman et al., 2004). One of the detectors was surrounded by a 0.63 mm thick Cd foil, the other by a 0.63 mm thick Sn foil. The Cd foil serves as a strong thermal neutron absorber, making the Cd-covered NS sensor an epithermal ($E_n > 0.4$ eV) neutron detector. The Sn-covered detector measures incident neutrons in the thermal ($E_n < 0.4$ eV) and epithermal ranges. The difference between the two detectors, combined with a precise knowledge of the energy-dependent detector response, allows for a measurement of the thermal neutron flux.

2. Radiation environments

The nominal radiation environment in lunar orbit consists primarily of solar charged particles and galactic cosmic rays (GCRs). The solar charged particles are protons and electrons, which follow a power-law distribution, with the magnitude and power depending on solar activity (Mewalt et al., 2005). The GCRs consist primarily of protons, with alpha particles comprising 6–7% of the total flux. The 4π GCR spectra can be described by the semi-empirical formula (McKinney et al., 2006)

$$g(T,\phi)=AT(T+2E_0)(T+m+\phi)^{-\gamma}/[(T+\phi)(T+2E_0+\phi)] \tag{2}$$

where A is a fitted parameter (1.24×10^{6} for protons), T is the kinetic energy per nucleon [MeV], E_0 is the rest energy of a nucleon [MeV], $m=a\,\exp(-bT)$, a and b are fitted parameters (a=780 MeV and $b=2.5\times10^{-4}$ for protons), ϕ is the time dependent solar modulation parameter [MV], and γ is a fitted parameter (2.65 for protons). Using measured proton flux data from the Energetic and Relativistic Nuclei and Electron (ERNE) instrument on the Solar and Heliospheric Observatory (SOHO), the parameters for the GCR and solar charged particle models can be fit to determine the charged particle environment at 1 AU as a function of time (Torsti et al., 1995). SOHO is located at the L1 Lagrange point, which is 15 million kilometers (0.01 AU) directly sunward of the Earth, making it an ideal position from which to measure the near-instantaneous protons fluxes in the Earth–Moon system.

During the LP trans-lunar cruise (January 7, 1998–January 12, 1998) the NS was collecting data and a constant background continuum signal was observed, which can be seen in Fig. 2. The absence of the 764-keV peak in the cruise spectrum demonstrates that the background in the detector during the cruise was from particles other than neutrons. The charged particle environment in trans-lunar space is dominated by protons and electrons, making

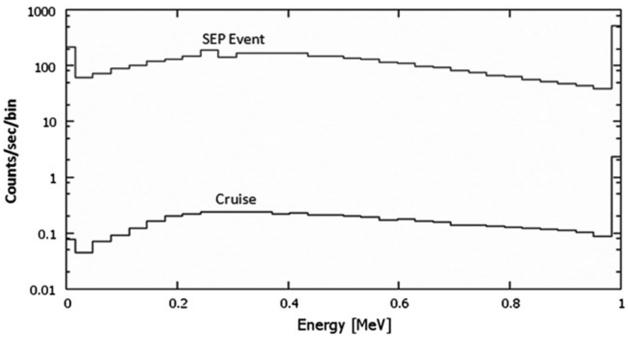

Fig. 2. Comparison of the Lunar Prospector Neutron Spectrometer background during the cruise phase, which represents the nominal proton radiation background, and the solar energetic particle event, in this case a class M solar flare, which occurred on April 20, 1998. During the solar event, the background increased by three orders of magnitude.