Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 40 (2007) 338–341
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

# The ionizing radiation environment on the moon

J.H. Adams [a], M. Bhattacharya [b,*], Z.W. Lin [b], G. Pendleton [c], J.W. Watts [a]

[a] Mail Stop VP62, NASA Marshall Space Flight Center, Huntsville, AL 35805, USA
[b] National Space Science and Technology Center, University of Alabama in Huntsville, Huntsville, AL 35805, USA
[c] Dynetics Incorporated, Huntsville, AL 35806, USA

Received 11 December 2006; received in revised form 8 May 2007; accepted 9 May 2007

**Abstract**

The ionizing radiation environment on the moon that contributes to the radiation hazard for astronauts consists of galactic cosmic rays, solar energetic particles and albedo particles (mainly neutrons), from the lunar surface. We present calculations of the effective dose rate due to lunar albedo neutrons. These calculations are based on GEANT4 Monte Carlo simulations of albedo neutron production on the moon. We compare our results with the Lunar Prospector (LP) fast neutron data. We also compare the effective dose rate from lunar albedo neutrons to that from galactic cosmic rays and solar energetic particles.


*Keywords:* Lunar albedo neutrons; Radiation environment on the moon

## 1. Introduction

The radiation hazard in deep space mainly comes from galactic cosmic rays (GCRs) and solar energetic particles (SEPs). On the Moon, albedo particles, mainly neutrons, are produced by the interactions of GCRs and SEPs with the Lunar crust. These neutrons contribute to the radiation environment on the lunar surface and in turn to the radiation hazard to astronauts.

The Neutron Spectrometer on board the Lunar Prospector (LP) mission measured lunar albedo neutrons at thermal (up to ~0.4 eV), epithermal (~0.4–100 eV) and fast neutron energies (0.6–8 MeV). The low-altitude data set on fast neutrons was taken between December 20, 1998 and July 28, 1999, and the resulting neutron energy spectrum has been published (Maurice et al., 2000). Counts of thermal and epithermal neutrons are also available (Feldman et al., 1998b,a).

We have compared the results from our calculations to the LP measurement of the fast neutron flux, and this gives us confidence in the absolute yield of fast neutrons from our calculations. We then use the albedo neutron flux over the entire energy range from our calculations to estimate the effective dose rate. We have also calculated the total neutron effective dose rate for GCR environments during solar minimum and solar maximum conditions. The results are compared with the corresponding effective dose rates from GCRs. We also compare neutron and SEP effective doses for the October 1989 SEP event.

## 2. Analysis

### 2.1. Lunar Prospector fast neutron data

The LP data on fast neutrons were published by Maurice et al. (2000) and are shown in Fig. 1. We have calculated the neutron spectra on the Moon using the GEANT4 code at the level of solar modulation that existed when the low-altitude LP measurements were made. This level was determined using the Badhwar–O'Neill Model (O'Neill, 2006) normalized to the cosmic ray proton and

* Corresponding author. Present address: National Nuclear Data Center, Building 197D, Brookhaven National Laboratory, Upton, NY 11973, USA. Tel.: +1 631 344 3839.
*E-mail address:* mbhattac@bnl.gov (M. Bhattacharya).

0273-1177/$30 © 2007 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2007.05.032

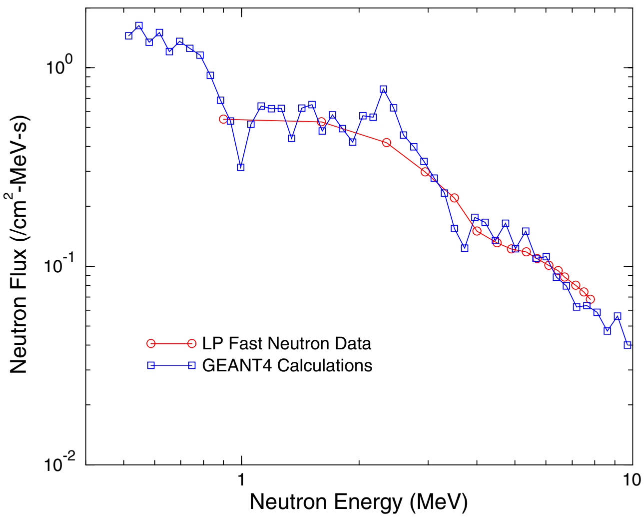


Fig. 1. Comparison of LP fast neutron data with GEANT4 calculations.

helium spectra measured by the BESS experiment (Wang et al., 2002) by adjusting the modulation parameter in the model. BESS measured the proton and helium spectra during a balloon flight on July 29–30, 1998 (Sanuki et al., 2000) and the proton spectrum was measured once again on August 11, 1999 (Asaoka et al., 2002). We found that the proton measurements in 1998 were best fit using a modulation parameter of 1000 MV and the 1999 proton measurements were best fit with a modulation parameter of 1050 MV. The fast neutron measurements were made on the LP mission between December 20, 1998 and July 28, 1999. The median modulation parameter during this period was 1034. This modulation parameter was used in the model to predict the proton spectrum when the LP albedo neutron measurements were made.

The BESS helium spectrum measurements in 1998 were best fit also using a modulation parameter of 1000 MV in the Badhwar–O'Neill model after using a correction (O'Neill, 2007). Using the proton interpolation as a guide, the modulation parameter was increased to 1034 MV for calculating the helium spectrum during the LP albedo neutron measurements.

Our results for fast neutrons are also shown in Fig. 1 for comparison. The calculated flux distribution agrees quite well with the data.

### 2.2. Albedo neutron flux for the entire energy range

We used our calculated albedo neutron spectrum over the entire energy range to extract the fraction of the effective dose rate contributed by the fast neutrons. We use the isotropic conversion factor from Bozkurt et al. (2000, 2001) to convert the neutron flux from Fig. 2 to the effective dose rate. Fig. 3 shows the differential effective dose rate multiplied by neutron energy. The area under the curve is proportional to the annual effective dose for the corresponding energy range. Our GEANT4 results show that fast neutrons from 0.6 MeV to 8 MeV contribute 37.1% of the total neutron effective dose rate and that 97.4% of the total effective dose rate comes from neutrons between 10 keV and 1 GeV. The thermal and epithermal neutrons contribute only 0.14% and 0.77% to the total effective dose rate, respectively, and are thus unimportant for estimating radiation hazard on the Moon. Even the higher thermal neutron fluxes anticipated in the permanently shadowed craters will not significantly increase the radiation hazard.

### 2.3. Effective dose rates from neutrons at other phases of the solar cycle

We also calculated the albedo neutron spectra resulting from GCR protons and Helium nuclei during the 1970

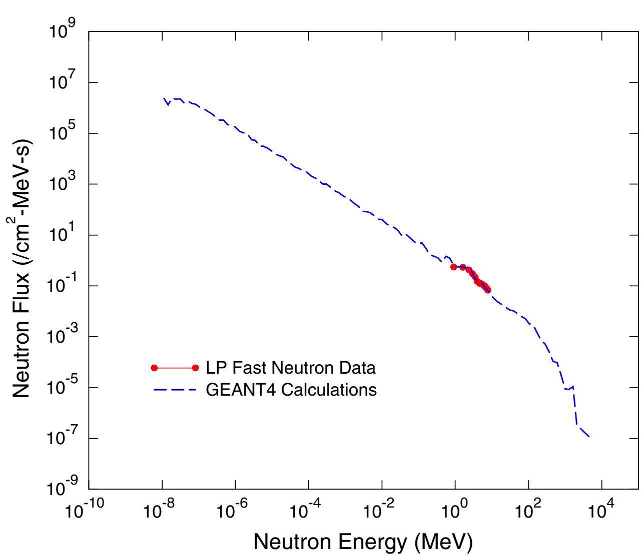


Fig. 2. GEANT4 calculations of neutron albedo for the entire energy range, compared to the LP fast neutron data.

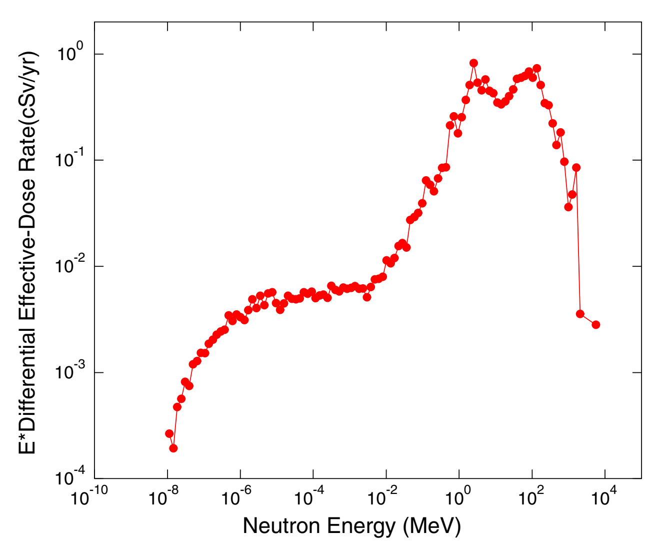


Fig. 3. Differential effective dose rate multiplied by neutron energy from GEANT4 calculations of neutron albedo during the LP data collection period: area under the curve is proportional to the effective dose rate.

solar maximum and the 1977 solar minimum conditions. The fast neutron spectra are shown in Fig. 4 and the differential effective dose rates are shown in Fig. 5. The effective dose rates are 1.98 cSv/yr for 1970 and 4.71 cSv/yr for 1977.

### 2.4. *Effective dose from lunar albedo neutrons produced by the October 1989 SEP event*

We used the SEP fluence spectrum for the October 1989 event that is given by Sauer et al. (1989) to compute the albedo neutron spectrum shown in Fig. 6. Using this spectrum (and assuming no anisotropy in the spectrum), we find that the effective dose from albedo neutrons for the October 1989 event to be 2.35 cSv.

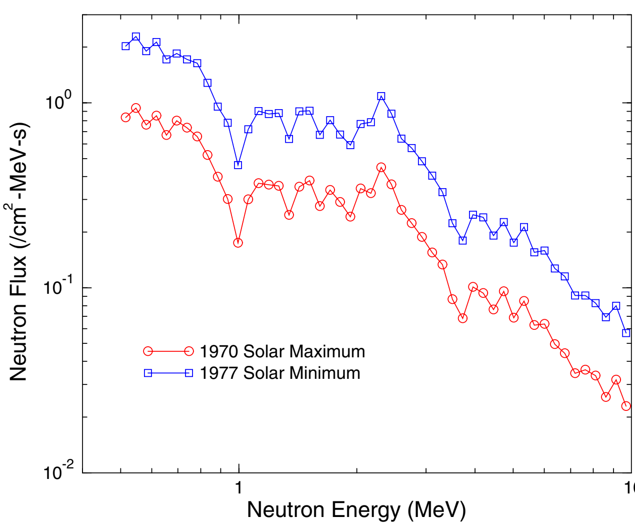


Fig. 4. Fast neutron fluxes for 1970 and 1977 GCR environments.

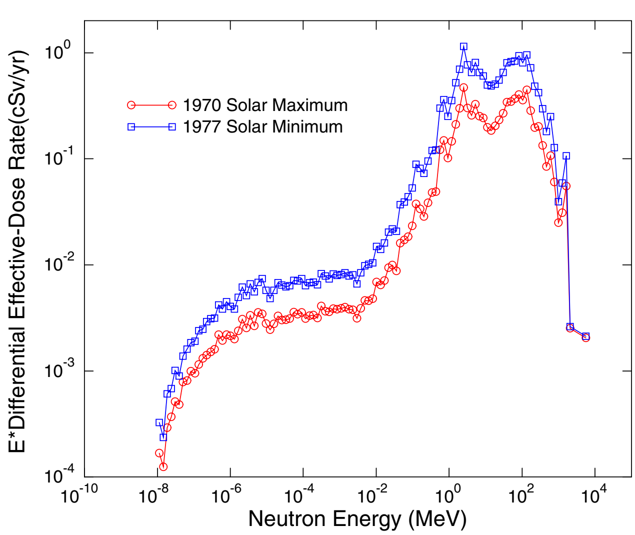


Fig. 5. Differential neutron effective dose rates multiplied by neutron energy for 1970 and 1977 GCR environments.

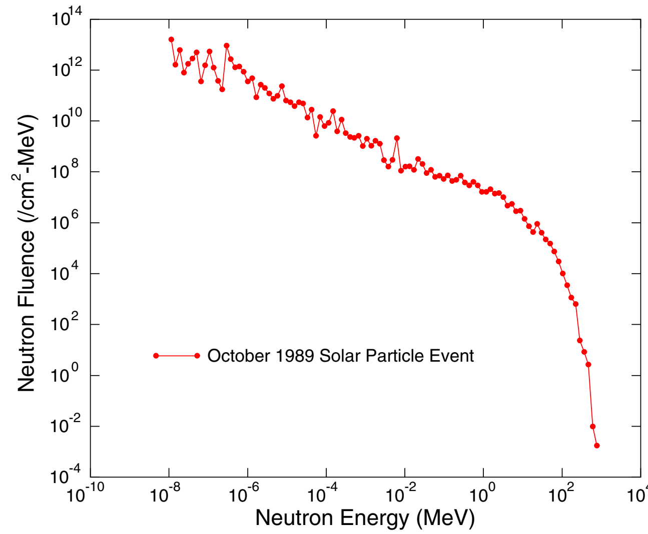


Fig. 6. Lunar albedo neutron spectrum due to the October 1989 solar particle event.

### 2.5. *Total effective dose rates*

GCRs and SEPs are the main sources of radiation on the Moon. The flux and therefore effective dose rate on the Moon from these sources are about half of that in deep space due to the self-blocking by the Moon. The effective dose rates for 1977 solar minimum and 1970 solar maximum GCR environments in deep space have been calculated by Hoff et al. (2002) for various depths in aluminum. In Table 1 we compare the effective dose from albedo neutrons with the corresponding doses from GCRs behind 1 g/cm$^2$ of aluminum during 1970 and 1977. It should be noted that there could be significant variations in the GCR effective dose rate calculations due to the choice of environment and the model dependence of the neutron flux to effective dose conversion factors.

Hoff et al. (2002) have also calculated the effective dose from the October 1989 SEP event behind various thicknesses of aluminum shielding. In Table 1 we also compare the effective dose from albedo neutrons during this event with the effective dose from SEPs during the same event behind 1 g/cm$^2$ of aluminum shielding.

Table 1
Comparison of the effective dose rates from GCRs and albedo neutrons during the 1970 solar maximum and the 1977 solar minimum

| | 1970 cSv/yr | 1977 cSv/yr | October 89 cSv |
|---|---|---|---|
| Neutrons | 1.98 | 4.71 | 2.35 |
| GCR/SEP | 8.95 | 24.40 | 96.40 |
| Total | 10.93 | 29.11 | 98.75 |
| % from neutrons | 18.1 | 16.2 | 2.4 |

Also shown is a comparison of the effective doses from the SEPs in the October 1989 event and the albedo neutrons generated by the SEPs during this event. The GCR and SEP effective doses were calculated behind 1 g/cm$^2$ of aluminum shielding.

## 3. Summary

We have calculated the lunar albedo neutron spectrum for the solar modulation level that existed when the Lunar Prospector data on fast neutrons were collected, the calculations agree quite well with these measurements. We calculated the albedo neutron spectra during the 1970 solar minimum and the 1977 solar maximum and also during the SEP event of October, 1989.

We converted these neutron spectra into effective doses and compared them with the effective doses due to GCRs and SEPs behind 1 $gm/cm^2$ of aluminum shielding. The results show that the contribution of albedo neutrons to the effective dose is small in all cases. The largest fractional contribution occurs at solar maximum. At solar maximum the neutron effective dose is 18% of the total effective dose. This is comparable to the uncertainty in the models for cosmic ray flux prediction. At solar minimum albedo neutrons contribute only 16% of the effective dose. During the October 1989 event only 2.4% of the dose came from albedo neutrons produced by SEP protons. We conclude that albedo neutrons make only a small contribution to the total radiation hazard on the moon.

## References

Asaoka, Y., Shikaze, Y., Abe, K., et al. Measurement of cosmic-ray low-energy antiproton and proton spectra in a transient period of solar field reversal. Phys. Rev. Lett. 88, 051101-1-051101-4, 2002.

Bozkurt, A., Chao, T.C., Xu, X.G. Fluence-to-dose conversion coefficients from monoenergetic neutrons below 20 MeV based on the VIP-man anatomical model. Phys. Med. Biol. 45, 3059–3079, 2000.

Bozkurt, A., Chao, T.C., Xu, X.G. Fluence-to-dose conversion coefficients based on the VIP-man anatomical model and MCNPX code for monoenergetic neutrons above 20 MeV. Health Phys. 81 (2), 184–202, 2001.

Feldman, W.C., Barraclough, B.L., Maurice, S., et al. Major compositional units of the moon: lunar prospector thermal and fast neutrons. Science 281, 1489–1493, 1998a.

Feldman, W.C., Maurice, S., Binder, A.B., et al. Fluxes of fast and epithermal neutrons from lunar prospector: evidence for water ice on lunar poles. Science 281, 1496–1500, 1998b.

Hoff, J.L., Townsend, L.W., Zapp, N. Space radiation protection: comparison of effective dose to bone marrow dose equivalent. J. Radiat. Res. 43 (Suppl.), S125–S128, 2002.

Maurice, S., Feldman, W.C., Lawrence, D.J., et al. High-energy neutrons from the Moon. J. Geophys. Res. 105, 20365–20376, 2000.

O'Neill, P. Badhwar–O'Neill galactic cosmic ray model update based on advanced composition explorer (ACE) energy spectra from 1997 to present. Adv. Space Res. 37, 1727–1733, 2006.

O'Neill, P., private communication, 2007.

Sanuki, T., Motoki, M., Matsumoto, H., et al. Precise measurement of cosmic-ray proton and helium spectra with the BESS spectrometer. ApJ 545, 1135–1142, 2000.

Sauer, H.H., Zwickl, R.D., Ness, M.J., Summary data for the Solar Energetic Particle Events of August through December 1989. Space Environmental Laboratory, National Oceanic and Atmospheric Administration Report, 1990.

Wang, J.Z., Seo, E.S., Anraku, K., et al. Measurement of cosmic-ray hydrogen and helium and their isotopic composition with the BESS experiment. ApJ 564, 244–259, 2002.