NUMERICAL SIMULATIONS OF COSMOGENIC NEUTRON PRODUCTION AND TRANSPORT IN PLANETARY SURFACES*.

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Summary: The numerical simulation code MCNPX was used to calculate the production and transport of cosmic-ray-produced neutrons in Mars and meteorites. These calculations help to understand the processes involved and the parameters that control the neutron fluxes. Results are presented here for neutrons in Mars and for the distribution of cosmic-ray neutrons and protons in a 50 cm-radius L-chondrite.

Introduction: In meteorites and planetary surfaces, galactic cosmic rays interact and produce many neutrons. The neutrons that escape from a planet can be used to study that surface's composition [1]. Neutrons measured by Mars Odyssey showed that water ice is fairly abundant in the top meter of Mars, especially near the poles [e.g., 2]. Good calculations for a range of concentrations and stratigraphies are needed to interpret measured leakage neutron fluxes.

Neutrons are the major source of most cosmic-ray-produced (cosmogenic) nuclides [e.g., 3], especially of the isotopes like ^{21}Ne used to study the cosmic-ray exposure records of meteorites. Neutron fluxes are sensitive to many parameters, such as size, depth, and composition [3,4]. The neutron distribution controls the production profiles of cosmogenic nuclides. As there are only a few measured cross sections for neutron-induced reactions, cosmogenic nuclides measured in samples exposed to a wide range of neutron spectra are needed to test calculated or estimated cross sections. The Earth's surface has a very soft spectrum with mainly low energy neutrons, but the computer codes commonly used are not good for the high-energy GCR particles that produce terrestrial cosmogenic nuclides away from the poles [5]. A better code to handle all cases is needed.

Calculations: The computer code MCNPX (Monte Carlo N Particle eXtended) [6,7] was used to calculate the interactions of galactic-cosmic-ray (GCR) particles with various extraterrestrial objects. These calculations are very similar to those done earlier using the LAHET Code System (LCS) [e.g., 4,5,8]. MCNPX contains improved versions of the LAHET and MCNP codes that are used in LCS. Unlike LCS, these two codes are automatically coupled in MCNPX, with neutrons below ~20 MeV made by LAHET calculations automatically being transported by MCNP. Some additional physics routines have been added to MCNPX, such as an improved code for very-high-energy particles, such as those at the Earth's equator with a geomagnetic cutoff of ~17 GeV.

The GCR spectrum averaged over a solar cycle as given in [4] was used for the incident GCR protons. An isotopic GCR flux was used to irradiate Mars or the meteoroid. For Mars, an average composition [8] was used for the non-volatile component. Concentrations of the volatiles CO_2 and H_2O can be varied to see their effects on the martian neutron fluxes. For the meteorite, the composition was that of an L-chondrite. The meteoroid had a 50 cm radius and a density of 3.7 g/cm^3. For both studies, the irradiated object was divided into many layers.

Results:

Martian neutrons. The neutron fluxes calculated in three layers (depths in g/cm^2) in Mars are shown in Fig. 1 for a surface with a 3% water content. The neutron fluxes increases with depth at first, then decreases at greater depths. The increase with depth varies with the energy of the neutron.

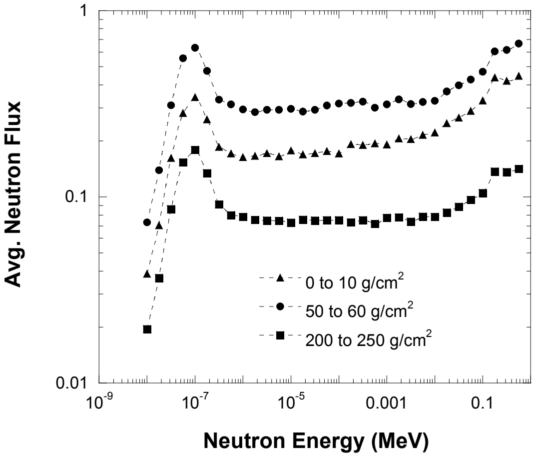

Fig. 1. Neutron fluxes in Mars averaged over 3 layers (depths in g/cm^2) for a 3% water content.

Fluxes in a meteorite. The neutron and proton energy spectra and depth distributions were calculated for several layers in a 50 cm-radius L-chondrite isotropically irradiated by GCR particles and monoenergetic protons with seven energies from 0.1 to

20 GeV. The results for the GCR spectrum are similar to those calculated for a similar stony meteorite by [4].

Protons with energies of 0.1 and 0.5 GeV do not have enough energy to pass through most parts of the meteorite, while protons with energies of about 1 GeV and higher can pass through the meteorite if they do not react. The fluxes of neutrons and protons inside the meteorite are shown in Fig. 2 for the energies of the monoenergetic protons and the spectrum of protons in the GCR. The number of protons and neutrons made by 1.6 GeV protons is the same as those for the GCR. This energy is close to the median GCR energy, 1.5 GeV, but is lower than the average energy in the GCR, 2.95 GeV, because some of the higher-energy protons pass through the meteorite without interacting and many of their secondaries escape. The average spectra of neutrons and protons below 1 GeV for GCR particles are between those for 1.0 and 2.5 GeV. However, for the GCR there are neutrons and protons with energies higher than 1.0 or 2.5 GeV.

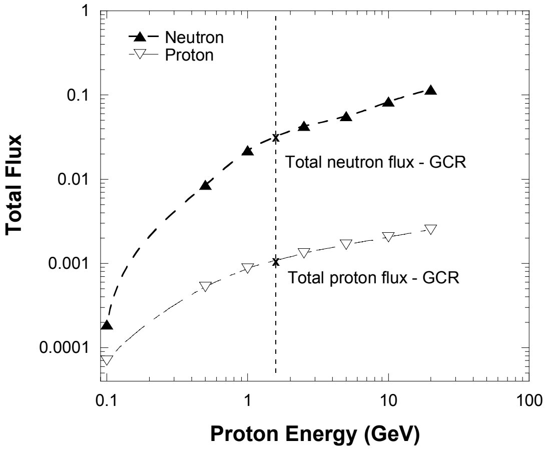

Fig. 2. Proton and neutron fluxes calculated in a 50 cm radius L-chondrite for monoenergetic incident protons and for the average GCR spectrum (x).

The depth distributions of protons produced by monoenergetic protons show the effects of the short range of 0.1 and 0.5 GeV protons. The higher-energy protons have a distribution similar to those for GCR particles with the main difference being the flux at all depths increases with the proton energy.

Fig. 3 shows the depth distributions of neutrons for the monoenergetic protons and the GCR spectrum. As with protons, the neutron fluxes increase with incident proton energy. However, the relative depth distribution of neutrons from 0.1 GeV protons is not very different from those for higher energy protons. The neutron energy spectrum for 0.1 GeV protons near the meteorite's center is mainly at low energies. These calculations indicate that the object's geometry is important in determining the depth distributions of neutrons and cosmogenic products.

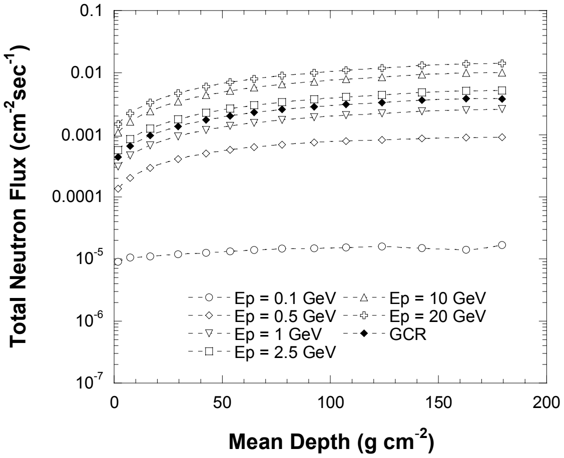

Fig. 3. Total neutron flux as a function of depth in a 50 cm-radius L-chondrite for 6 proton energies (open symbols) and the GCR spectrum (filled diamonds).

Conclusions: These calculations with the MCNPX code numerically simulating the interactions of cosmic-ray particles with planetary matter show its importance in calculating production of cosmogenic products and in understanding the physics of the processes involved. Tests of MCNPX calculations with measured cosmogenic neutrons and nuclides are needed before the routine use of MCNPX for planetary applications, such as gamma-ray fluxes from Mars.

References: [1] Drake D. M. et al. (1988) *J. Geophys. Res. 93,* 6353-6368. [2] Mitrofanov I. et al. (2002) *Science 297,* 78-81. [3] Reedy R. C. et al. (1993) *LPS XXIV,* 1195-1196. [4] Masarik J. and Reedy R. C. (1994) *Geochim. Cosmochim. Acta 58,* 5307-5317. [5] Masarik J. and Reedy R. C. (1995) *Earth Planet. Sci. Lett. 136,* 381-395. [6] Waters L. S., ed. (2002) *MCNPX User's Manual, Version 2.3.0,* Los Alamos National Laboratory report LA-UR-02-2607. [7] Hendricks J. S. et al. (2002) RPSD2002, American Nuclear Society, Santa Fe, NM, Los Alamos report LA-UR-02-0642. [8] Masarik J. and Reedy R. C. (1996) *J. Geophys. Res. 101,* 18891-18912.

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