COSMOGENIC-NUCLIDE DEPTH PROFILES IN THE LUNAR SURFACE.*

R. C. Reedy and J. Masarik, Astrophysics and Radiation Measurement Group, Mail Stop D436, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

Depth-dependent production rates of ^{10}Be, ^{26}Al, ^{36}Cl and ^{53}Mn in the lunar surface were calculated using evaluated cross sections and the LAHET Code System for particle fluxes. Good agreement with experimental data were obtained for all investigated radionuclides down to 400 g/cm^2 for a primary galactic-cosmic-ray particle flux of 4.56 nucleons/cm^2/s. The nature of the reactions making a nuclide strongly affects the amount of the production-rate increase from the surface to the peak and the depth of this peak but has little effect on the rate of decrease below 200 g/cm^2.

The study of cosmogenic nuclides in extraterrestrial bodies allows us to study the histories of cosmic rays and the irradiated object. In order to use cosmogenic nuclides as such a tool, it is essential to understand how production rates depend on the shielding of the sample in which the nuclide is measured. Because of their low energies, most solar cosmic rays (SCR) are stopped by ionization loses in the outermost few g/cm^2. We did not simulate the contribution of SCR to the total production rates and therefore have underestimated nuclide production near the surface. The galactic cosmic rays (GCR) have much higher energies and penetrate very deep inside the irradiated body and produce many secondary particles that contribute to nuclide production. The nuclear processes involved in the interaction of GCR particles with matter are simulated in our model with the LAHET Code System (LCS) [1], which is a system of coupled Monte Carlo codes that treats the relevant physical processes of particle production and transport. LCS and its adaptation to meteorite applications are described in [2]. Production rates calculated in meteorites using LCS-calculated fluxes have agreed well with various measurements [2–4].

We simulated the irradiation of the lunar surface with an isotropic GCR particles flux of 1 proton/cm^2/s with an energy distribution corresponding to the GCR primary particle flux averaged over a solar cycle. The Moon was modeled as a sphere with the average lunar radius, and the bulk composition and density were from the Apollo 15 deep-drill core (15001/6). To map the depth dependence of production rates, we divided the model sphere into concentric shells with thickness 6 g/cm^2. In each shell, neutron and proton fluxes were calculated. Simulation of 50,000 primary GCR particles gives calculated particle fluxes with statistical errors less than 3%. Having calculated the particle fluxes, the production rates of cosmogenic nuclides were calculated by integrating over energy the product of these fluxes with cross sections for the nuclear reactions making the investigated nuclide [2]. Cross sections were those evaluated for extraterrestrial studies: ^{10}Be [5], ^{26}Al [6], ^{36}Cl (like in [7] but with 0.8 of all Ca cross sections below 1 GeV), and ^{53}Mn [8,9].

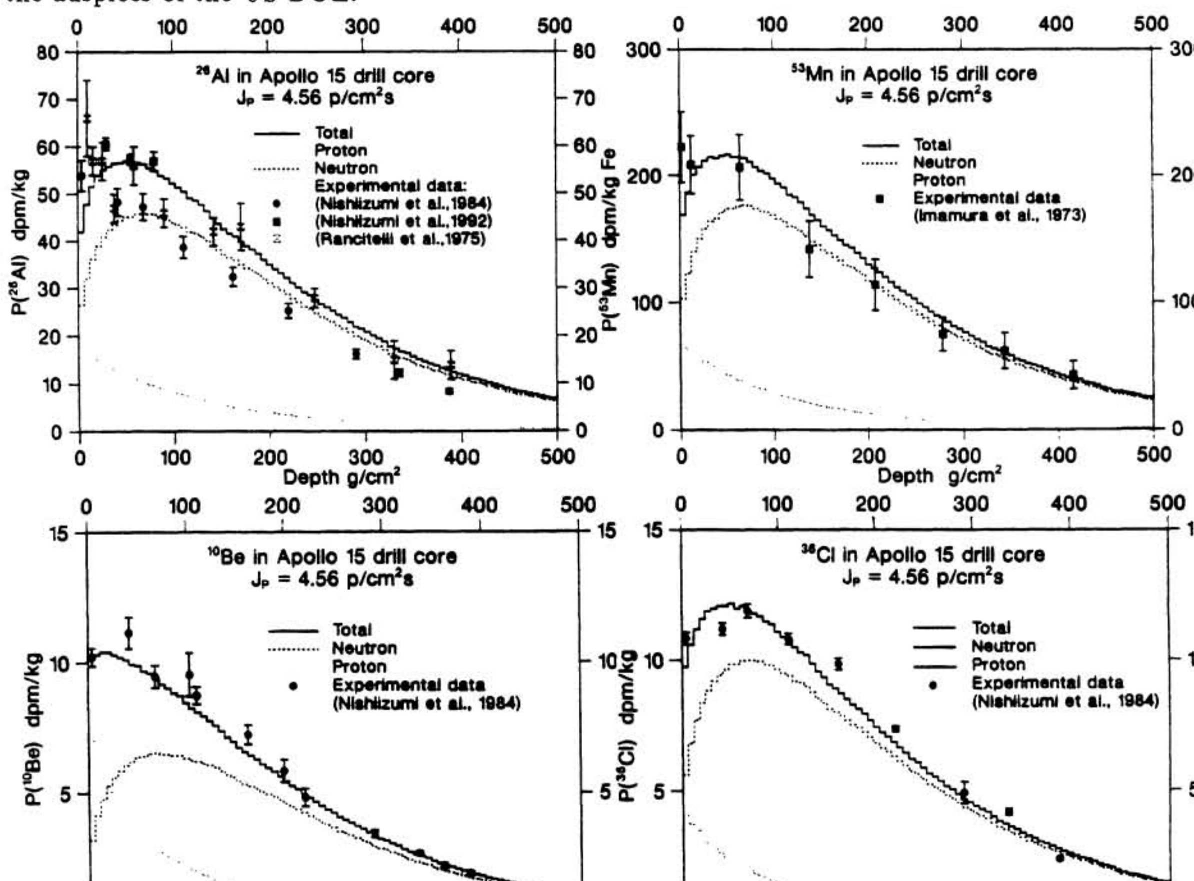
We first determined the flux of GCR particles over the few last Myr by fitting the calculated depth profiles for the production of ^{26}Al and ^{53}Mn in the Apollo 15 drill core to the experimental data [10–12] (cf., Figs. 1 and 2). The ^{26}Al measurements of [13] are ~0.81 of the others. Fairly good agreement was found over the whole depth region with an effective incident GCR particle flux of 4.56 protons/cm^2/s. The agreement with the ^{10}Be and ^{36}Cl lunar measurements [14] are also fairly good (Figs. 3–4). This flux is slightly less than the one of 4.8 protons/cm^2/s we found for these radionuclides in meteorites [3], implying that the average GCR flux at meteorites are ~5% greater than that at 1 AU. This effective flux includes contributions from the alpha particles in the GCR (~13%) [2] and is equivalent to a primary GCR proton flux of 3.04 protons/cm^2/s. Our GCR flux of 4.56 protons/cm^2/s is slightly less than the lunar ones of [15] (4.72) and [16] (5.5) calculated with a similar code, the differences probably due to the cross sections used.

The figures present the total calculated production rates and the contributions of protons and neutrons. Contributions of other particles (e.g., pions) are negligible [2]. Neutron production is dominant for all depths and nuclides except for ^{10}Be near the surface. The neutron contributions vary from ~60% at the surface (only ~30% for ^{10}Be) to about 90% at depths $\gtrsim$400 g/cm^2.

A characteristic feature of all production-rate-versus-depth profiles is an increase from the surface to a peak value and then an approximately exponential decrease to greater depths. The depth of the peak production and the steepness of increase from surface to the peak are determined by characteristics of the nuclear reactions making the nuclide [17]. The highest energy product investigated in this study, ^{10}Be, has a peak production rate at a depth about 20 g/cm^2 and the difference between peak and near surface production rates is less than 1 atom/min/kg. The flat experimental ^{10}Be profile [18] together with our calculations imply that the SCR contribution to the ^{10}Be production is ~1 atom/min/kg. The steepest increase from surface to the peak production rate is observed for ^{26}Al, which like ^{36}Cl and ^{53}Mn reach peak production rates near 50 g/cm^2. The e-folding lengths for depths of 200–450 g/cm^2 are 179 g/cm^2 for ^{10}Be and ^{53}Mn and 182 g/cm^2 for ^{26}Al and ^{36}Cl, in very good agreement with measured values [13,14]. Over the depth range of 150–450 g/cm^2, the e-folding lengths of these four radionuclides decreases with increasing depth, with the biggest rate of change nearest the surface and the least change for ^{10}Be.

These calculations for the production of cosmogenic nuclides are in good agreement with measured data and with other model calculations [8,15] with respect to the absolute magnitude as well as the shape. Our inferred GCR flux for the last few Myr are similar to modern fluxes, indicating no significant change of the GCR intensity during the last few million years.

References [1] Prael R.E. and Lichtenstein H. (1989) *Los Alamos Report LA-UR-89-3014*. [2] Masarik J. and Reedy R.C. (1994) *GCA*, submitted. [3] Reedy R.C. *et al.* (1993) *LPS XXIV*, p. 1195. [4] Michlovich E.S. *et al.* (1994) *JGR*, submitted. [5] Tuniz C. *et al.* (1984) *GCA* **48**, 1867. [6] Reedy R.C. (1987) *NIM* **B29**, 251. [7] Nishiizumi K. *et al.* (1989) *PLPSC-19*, p. 305. [8] Reedy R.C. and Arnold J.R. (1972) *JGR* **77**, 537. [9] Nishiizumi K. (1988) (priv. comm.). [10] Rancitelli L.A. *et al.* (1975) *PLSC-6*, p. 1891. [11] Nishiizumi K. (1992) (priv. comm.). [12] Imamura M. *et al.* (1973) *EPSL* **20**, 107. [13] Nishiizumi K. *et al.* (1984) *EPSL* **70**, 164. [14] Nishiizumi K. *et al.* (1984) *EPSL* **70**, 157. [15] Michel R. *et al.* (1991) *Meteoritics* **26**, 221. [16] Dagge G. *et al.* (1991) *PLPSC-21*, p. 425. [17] Masarik J. and Reedy R.C. (1993) *Meteoritics* **28**, 391. [18] Nishiizumi K. *et al.* (1988) *PLPSC-18*, p. 79. * Work supported by NASA and done under the auspices of the US DOE.



Figs. 1–4. Calculated and measured production rates in the Apollo 15 deep drill core.