# COSMOGENIC-NUCLIDE DEPTH PROFILES IN LUNAR ROCKS.*

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Depth-dependent production rates of $^{10}$Be, $^{21}$Ne, $^{26}$Al, $^{36}$Cl and $^{53}$Mn in 2-cm vertical cores in hemispherical lunar rocks of various radii on the Moon's surface were calculated using evaluated cross sections and the LAHET Code System for particle fluxes. Similar calculations for meteorites and lunar soil cores have given good agreement with measurements. The nature of the reactions making a nuclide affects changes in production rates for rock geometries relative to a slab, but production rates for rocks with radii less than about 15 cm tended to be lower, those with radii of about 20–100 cm tend to be higher, and those with radii greater than about 1 meter are similar to those for a slab. The shapes of these profiles near the very surface are not very different from those for a slab. Thus the question of where is the solar-proton-produced $^{10}$Be expected in lunar rocks is not answered by explicitly considering the geometry of a lunar rock on the Moon's surface.

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 of cosmogenic nuclides depend on the sample's shielding (the sample's location in the object and the object's size and geometry). Much work has been done on production rates as a function of shielding, but almost all of this work has been for simple spherical or slab geometries.

Two types of cosmic rays are important in lunar rocks, galactic and solar [1]. Because of their low energies, most solar cosmic rays (SCR), which are almost entirely protons, are stopped by ionization energy losses in the outermost few g/cm$^2$. 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. To study the SCR contributions in lunar samples, the GCR contributions must be removed from measured concentration-versus-depth profiles. Often the SCR component near the surface is much higher than the GCR component, and some uncertainty in the GCR component does not seriously affect the derived SCR component. However, some cosmogenic nuclides, especially $^{10}$Be, have low production rates by solar protons, and it has been very hard to infer the SCR component from the measured $^{10}$Be data [e.g., 2,3]. For nuclides like $^{10}$Be, better GCR profiles are needed for SCR studies. Existing lunar GCR calculations [e.g., 1,4] only considered a slab geometry. However, most lunar rocks extend above the lunar surface, and thus have an exposure geometry difference from a flat $2\pi$ slab.

The nuclear processes involved in the interaction of GCR particles with the Moon were simulated with the LAHET Code System (LCS), which is a system of 3-D, coupled Monte Carlo codes that treat the relevant physical processes of particle production and transport. LCS and its adaptation to meteorite applications are described in [5]. Production rates calculated for meteorites and lunar cores using LCS-calculated fluxes have agreed well with various measurements [e.g., 4–7]. Preliminary calculations for production rates in hemispherical shells for rocks on the Moon showed differences relative to production rates in slabs [8]. However, most lunar-rock measurements are for vertical profiles and not whole hemishells.

We simulated the irradiation of hemispherical rocks on the lunar surface with an isotropic GCR-particle flux of 4.56 nucleons/cm$^2$/s with an energy distribution corresponding to the GCR primary particle flux averaged over a solar cycle, as determined from nuclides measured in lunar cores [4]. Production rates were calculated for a series of depths in a vertical cylinder of 2-cm diameter down the center of the rock. The composition of lunar rock 68815 [2] and a density of 2.3 g/cm$^3$ were used for these calculations for particle transport and production. Having calculated the particle fluxes with LCS, 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 [5]. Cross sections were those evaluated for the study of radionuclides in lunar cores [4] or for noble gases in lunar rock 68815 [3].

The calculated production profiles for $^{10}$Be, $^{21}$Ne, $^{26}$Al, and $^{53}$Mn in a 2-cm vertical core in hemishells of various radii on the lunar surface are shown in Figs. 1–4. The calculated profiles for $^{36}$Cl are very similar to those for $^{26}$Al. In all cases, the calculated production rates for hemishells with radii less than ~15 cm (~35 g/cm$^2$) tend to be below those for a slab (1738 km). For radii of ~20–100 cm (~46–230 g/cm$^2$), the rock's production rates are higher than those for the same depths in a slab. For radii $\gtrsim$1 meter ($\gtrsim$230 g/cm$^2$), the calculated production rates in the rock as a function of depth are similar to those in a slab. The largest differences from a slab are for radii of ~30–45 cm (~70–100 g/cm$^2$), which are roughly dimensions for most interactions of energetic nuclear particles. These lunar-rock GCR production rates cannot be tested by simply comparing to measurements because of the presence of SCR production. $^{10}$Be has the least SCR production.

In studies of $^{10}$Be concentration-versus-depth profiles in lunar rock 68815 [2,3], the estimated GCR production profiles used were very similar to the measured profiles, leaving very little that could be assigned to SCR production. If the GCR production profile in lunar rock 68815 was steeper, then there would be more excess in the measured-minus-GCR profile for SCR production. However, the calculated GCR $^{10}$Be profiles for rocks are not different from those calculated for a slab, and the production rates at depth of about 5 g/cm$^2$ are only ~0.2 atoms/min/kg higher than those at the very surface. The surface production rates for SCR-produced $^{10}$Be is expected to be ~1 atom/min/kg or higher [2]. Thus the question of where is the expected SCR production of $^{10}$Be is still open. These calculations show that analyses of other SCR-produced nuclides is not sensitive to the exact geometry used for the rock.

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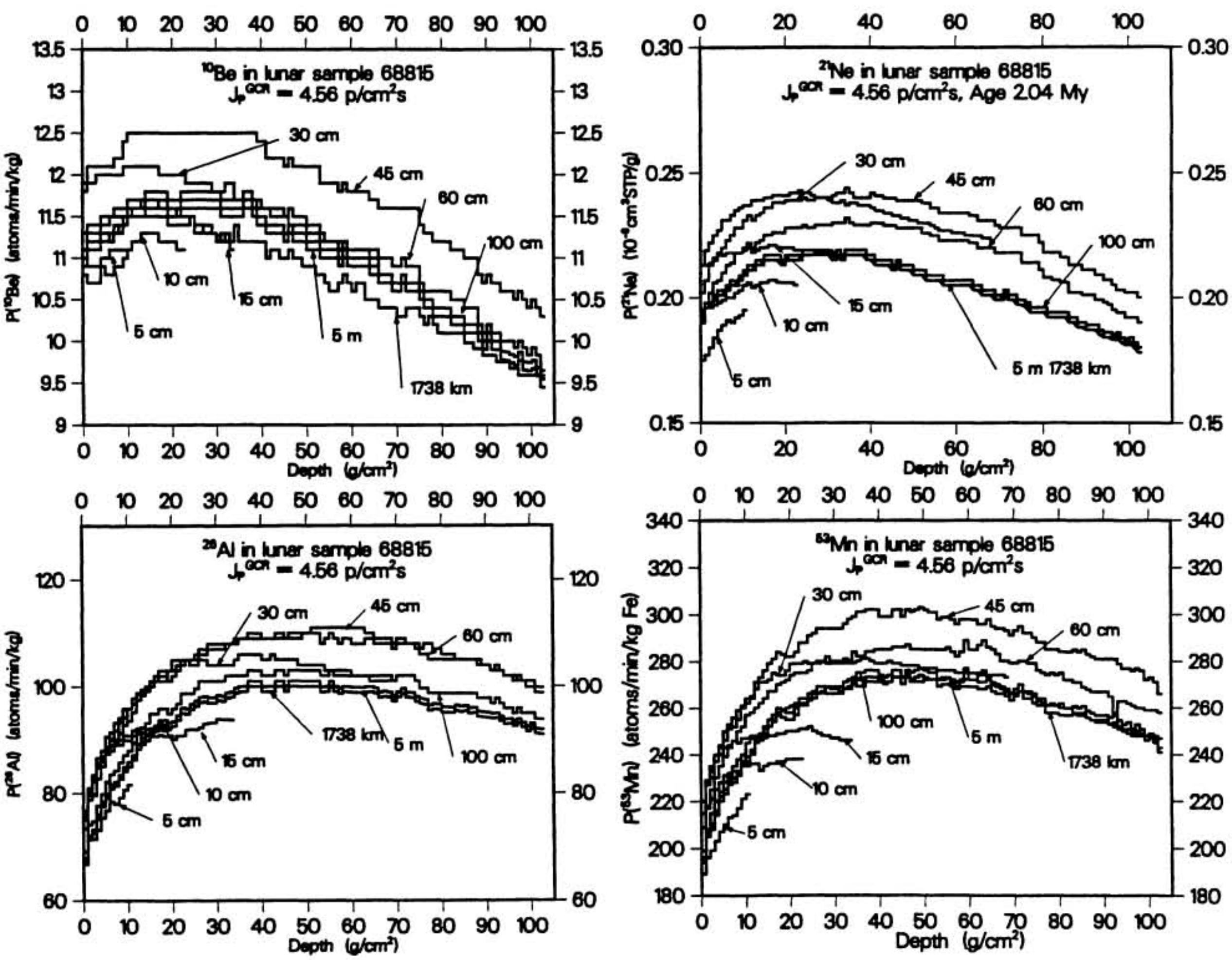


Figs. 1–4. Calculated cosmogenic-nuclide production rates versus depth for a 2-cm vertical core in hemispherical rocks of various radii on the lunar surface using the composition of rock 68815.