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COSMOGENIC NUCLIDES: OBSERVABLE EFFECTS OF MARTIAN VOLATILES*

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Cosmic-ray-produced (cosmogenic) nuclides in returned martian samples could be used to study the amounts and distributions of volatiles in the recent past on Mars. In planning for the Gamma-Ray Spectrometer experiment that is scheduled to fly on the Mars Observer, we have done many calculations on the nuclear reactions that should occur in the martian surface, studying especially the production and transport of neutrons. We have found that three aspects of Mars can very significantly affect the production of cosmogenic products in Mars: the martian atmosphere and the presence of H_2O in or CO_2 on the surface of Mars. These volatile components can greatly affect the energy and spatial distributions of neutrons, especially those with thermal or near thermal energies, in the surface of Mars (1). In turn, these neutrons produce many cosmogenic nuclides that can be observed in samples returned from Mars.

Most cosmogenic nuclides are produced by secondary neutrons made by galactic-cosmic-ray (GCR) interactions, although a few (e.g., ^{10}Be) are mainly made by the primary GCR particles (2). The energy and spatial distributions of these neutrons are especially sensitive to certain elements with special nuclear properties, such as hydrogen and carbon (which effectively thermalize energetic neutrons). Neutron-transport calculations for objects with no atmosphere (3-5) showed that hydrogen significantly changed the depth and energy distributions of low-energy (thermal and epithermal) neutrons, increasing their flux and raising the depth of their peak intensity. However, until recently (1,6), no calculations had been done for neutron transport in Mars with its 16-g/cm^2-thick atmosphere of almost pure carbon dioxide and the variable contents of CO_2 frost and H_2O in or on its surface.

The equilibrium distribution of neutrons in Mars was calculated using the One-Dimensional, Diffusion-Accelerated, Neutral-Particle Transport (ONEDANT) code (1). The ONEDANT code was modified to include the effects of gravity and the beta decay of low-energy neutrons that escape from and then return to the surface of Mars (7). A 16-g/cm^2 atmosphere was included in all of the calculations, and the compositions of the atmosphere and surface soil as determined by the Viking landers were used in all the calculations. Many special cases involving variable amounts of and depths for H_2O or thicknesses of CO_2 frost on the surface were run. The equilibrium distributions of neutrons calculated by ONEDANT in the martian surface agreed with those from an independent set of calculations (6). Hydrogen in the martian surface rapidly thermalized neutrons and shifted their energy and depth distributions. Carbon dioxide as frost or in the atmosphere attenuated the intensity of incident cosmic-ray particles, moderated fast neutrons, and built a reservoir of low-energy neutrons that leaked back into the martian surface. The combined effects of the martian atmosphere and H_2O on the neutron distribution in Mars are illustrated in Fig. 1, which shows the neutron-capture ("GAMMA") profiles for several water contents of the surface. Relatively high water contents result in distinctive shapes for the martian neutron-capture profile not seen in other calculations with high hydrogen contents (3-5), especially just below the atmosphere-surface boundary.

To unfold the cosmic-ray record in martian samples, many products with various half-lives made by cosmic-ray particles with different energies would need to be measured. For example, ^{10}Be made by high-energy reactions, ^{26}Al made by fast neutrons, and ^{36}Cl made by neutron-capture reactions with relatively abundant martian chlorine could be used to establish the average cosmic-ray particle environment in the martian surface over the last million years (the approximate half-lives of these three long-lived radionuclides). If the systematics of these radioactivities differ from those observed for short-lived radionuclides, such as spallogenic 2.6-year ^{22}Na and neutron-capture-produced 5.27-year ^{60}Co, then we could possibly infer that changes had occurred in the martian climate (CO_2 thickness or surface hydrogen content) over the last million years. Stable cosmogenic nuclides, such as ^{21}Ne, high-energy-produced ^{3}He, and ^{36}Ar (mainly from the decay of neutron-capture-produced ^{36}Cl) could extend this comparison to longer time periods. Such studies would be in addition to those done now with cosmogenic nuclides in lunar samples, such as determining exposure ages and gardening rates of the regolith (8).

Both cores in the martian regolith down to depths of at least a meter and surface rocks would be needed to unfold the various cosmic-ray records. Care would be needed to prevent the loss of certain cosmogenic products that are volatile, such as chlorine or the noble gases, from the returned samples (9). In interpreting the cosmogenic-nuclide measurements, the sample's location and its chemical composition, especially its (and the surrounding) hydrogen content, need to be known (9).

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Figure 1. The relative rates for the capture of low-energy (thermal and epithermal) neutrons in Mars as a function of depth (the top 16 g cm^{-2} is the atmosphere) for water contents of 0, 1, 50, and 100%. Note the enhanced rates just below the atmosphere-surface boundary for high water contents. The sudden, sharp decreases below 300 g cm^{-2} are artifacts of the calculations.