NUMERICAL SIMULATIONS OF GAMMA-RAY EMISSION FROM THE MARTIAN SURFACE*; J. Masarik and R. C. Reedy, Astrophysics and Radiation Measurement Group, Mail Stop D436, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

The fluxes of natural and cosmic-ray-produced gamma rays escaping from Mars were calculated for 8 water contents of the surface and 6 thicknesses of the atmosphere. The water content and atmospheric thickness both strongly affect the fluxes of gamma-ray escaping from Mars.

The γ rays escaping from planetary bodies such as the Moon, Mars, asteroids, and comets can be used for mapping the elemental composition of the surface's top few tens of centimeters [1]. Low-resolution spectrometers measured γ rays at the Moon on Apollos 15 and 16 and at Mars on Mars 5 and Phobos 2. A high-resolution γ-ray spectrometer was on Mars Observer [2], and the martian γ-ray fluxes reported here were calculated for the inversion of measured martian γ-ray fluxes to elemental compositions. Although Mars Observer is lost, γ-ray spectrometers are scheduled to be flown on Mars-94 and possibly other orbital and surface missions to Mars.

Elements that can be mapped using γ-ray spectroscopy include all major ones, many minor ones, and some trace ones [1]. Gamma-ray emission from planetary surfaces results from several processes, the most important being γ rays from the decay of the major natural radioactive elements and by nuclear reactions of primary and secondary cosmic-ray particles. Gamma rays used for most elemental studies are made by inelastic-scattering reactions of neutrons with a few MeV of energy or by neutron-capture reactions near thermal energies. Other γ-ray sources can create backgrounds or interferences. Some relative martian γ-ray fluxes calculated with a neutron-transport code by [3] examined the effects of hydrogen on γ-ray fluxes.

We calculated the fluxes of 80 γ rays made by the decay of naturally-occurring Th, U, and ^{40}K for 6 atmospheric thicknesses. Around the average martian atmospheric thickness of 15 g/cm^2, a thickness increase of $\sim$8 g/cm^2 reduces escaping γ-ray fluxes by a factor of about 2, with greater reduction for γ-ray energies below $\sim$0.5 MeV. Measurements of γ rays with both low and high energies (e.g., 238 and 2614 keV ones of Th) can be used to infer atmospheric thickness.

Using the LAHET Code System (LCS) for the simulation of galactic-cosmic-ray (GCR) interactions with Mars, we calculated the intensities of 243 γ-ray lines produced in the martian soil via nonelastic scattering reactions and 74 lines made by neutron-capture reactions. LCS is a system of general-purpose, continuous-energy, generalized-geometry, time-dependent, off-line coupled Monte Carlo computer codes that treat the relevant physical processes of particle production and transport. This code system and its successful application to meteorites are discussed in [4]. A similar code system was used by [5] to calculate fluxes of several lunar and martian γ rays. Our calculated lunar γ-ray fluxes were slightly higher than those of [6] because of higher LCS-calculated neutron fluxes below a few MeV.

An isotropic GCR irradiation by 4.56 protons/cm^2/s, corresponding to the GCR primary particle spectrum averaged over a solar cycle, of a sphere with the average radius of Mars (3390 km) was simulated. In the assumed bulk chemical composition [2], the water content was varied from zero to 90%. The elemental weight fractions used for the martian atmosphere were C=0.2639, N=0.0174, O=0.7040, and Ar=0.0147, based on the mole (volume) abundances of [7]. The thickness of the atmosphere was varied from 0 to 25 g/cm^2. The decrease of the atmospheric density with increasing altitude for the LCS calculations used a scale height of 10.8 km [8], although our γ-ray fluxes are not sensitive to details of the atmospheric height-thickness distribution. Using a density of 1 g/cm^3 for the atmosphere in the LCS calculations, the γ-ray fluxes increased by $\sim$10% compared to those calculated with the observed scale height.

Both atmosphere and soil were divided into concentric shells, with many shells near surface and fewer shells at greater depths. Neutron and proton fluxes were calculated for each shell. Production rates for neutron-capture reactions were calculated by LCS. Production rates of nonelastic γ rays were calculated using LCS-calculated particle fluxes and the cross sections of [6], analogous to that done for nuclides [4]. We are not concerned with scattered γ rays, which only contribute to the continuum, but only with the γ rays that undergo no interactions before escaping from Mars. Thus, having calculated the production rates of a γ ray at various depths, we used exponential mass attenuation coefficients for that γ ray to calculate the flux escaping from Mars and reaching a 400-km spacecraft altitude without changing energy. This integral over depth was done down to 400 g/cm^2, a depth below which very few γ rays escape. Our γ-ray fluxes agree well with those of L. Evans [priv. comm., 1993] but are only in fair agreement with those of [5] for natural and capture γ rays and, if our incident GCR flux is used, for inelastic γ rays.

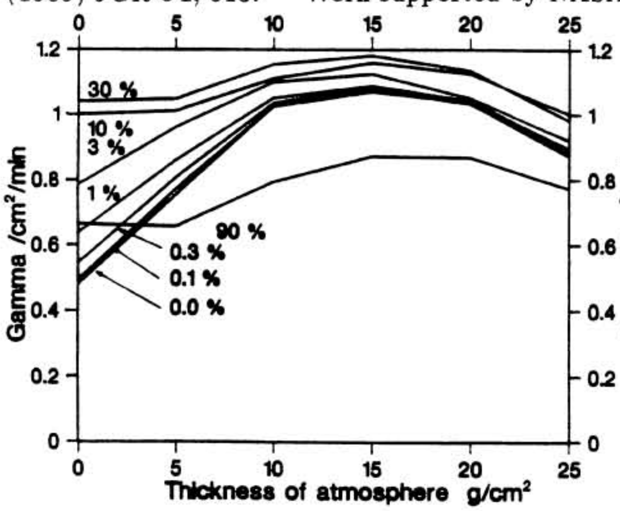
Our simulations for martian γ ray fluxes span several likely martian situations. Particle fluxes in Mars are affected by the particle-transport properties of martian soil, especially to the soil's H content, and the martian atmosphere [9]. As H is added to the martian soil, its properties for neutron transport are changed, with fast and epithermal neutrons more rapidly slowed to thermal energies. This results in an enhanced thermal flux and a shallower peaking of that flux for soils with higher H contents [1]. Hydrogen and certain other elements like iron strongly absorb thermal neutrons, and increases in their concentrations depress thermal-neutron fluxes. Shifts of neutron fluxes in the martian surface are also calculated for increased atmosphere thickness [9].

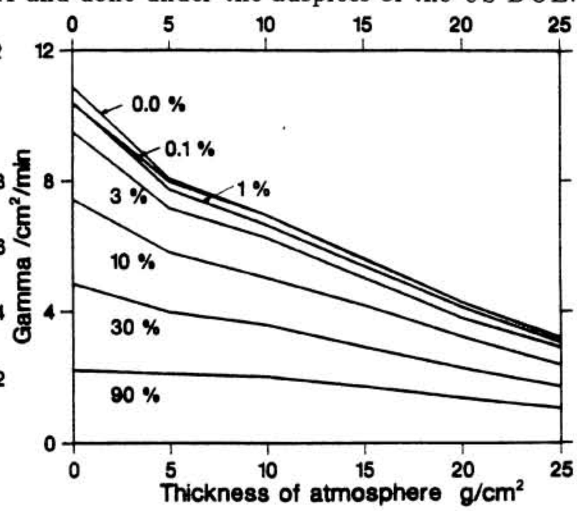
The influence of hydrogen and atmospheric thickness on fluxes of γ rays made by neutron-capture reactions is demonstrated in Fig. 1 for the 4934-keV γ ray made by the $^{28}Si(n,\gamma)^{29}Si$ reaction. The trends in Fig. 1 are representative for all γ-ray lines produced by neutron-capture reactions. With the increase of hydrogen content in martian soil, the flux gradually increases, until some critical value (~30% water), where the influence of thermal-neutron absorption begins to play a substantial role leading to the decrease of γ-ray flux. An increase of γ-ray flux with the increase of atmosphere thickness is also visible up to thicknesses of 15 g/cm^2. Fluxes of this γ ray at the martian surface increase up to an atmospheric thickness of ~25 g/cm^2 and tend to decrease with increasing water content.

Fig. 2 shows the 1779-keV γ ray from ^{28}Si produced by inelastic-scattering reactions. The flux monotonically decreases with increasing atmospheric thickness and with the increase of hydrogen in martian soil because increased thermalization rates are depleting the fast neutron flux that produces these γ rays. Fluxes of this γ ray at the surface decreases with increasing water content but increase from the case of no atmosphere to peak fluxes for ~5–15 g/cm^2-thick atmospheres but then begins to decrease.

Our simulations of the intensities of martian γ-rays produced by the interactions of galactic cosmic rays with the Mars indicate that the analyses of martian γ-ray spectra require a knowledge of the hydrogen content of the soil and the atmospheric thickness, although certain γ rays can be used to infer these quantities. Gamma-ray fluxes at the martian surface are higher than those above the atmosphere and those for no atmosphere. The relations between γ-ray fluxes at the surface and at orbit can be complicated, especially for neutron-capture.

References: [1] Evans L.G *et al.* (1993) in: *Remote Geochemical Analysis*, Cambridge Press, p. 167. [2] Boynton W.V. *et al.* (1992) *JGR* **97**, 7681. [3] Evans L.G. and Squyres S.W. (1987) *JGR* **92**, 9153. [4] Masarik J. and Reedy R.C. (1994) *GCA* (submitted). [5] Dagge G. *et al.* (1991) *PLPSC-21*, p. 425. [6] Reedy R.C. (1978) *PLPSC-9*, p. 2961. [7] Owen T. *et al.* (1977) *JGR* **82**, 4635. [8] Zurek R.W. *et al.* (1992) in: *Mars*, Univ. Arizona Press, p. 835. [9] Feldman W.C. *et al.* (1989) *JGR* **94**, 513. * Work supported by NASA and done under the auspices of the US DOE.





Figs. 1–2. Fluxes at a 400-km altitude above Mars of the 4934-keV γ ray made by the $^{28}Si(n,\gamma)^{29}Si$ neutron-capture reaction (left) and the 1779-keV γ ray made by the $^{28}Si(n,n\gamma)^{28}Si$ inelastic-scattering reaction (right) as a function of atmospheric thickness. Curves are for different water contents of the martian surface.