Space Radiation Dose Estimates on the Surface of Mars

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Abstract

A FUTURE goal of the U.S. space program is a commitment to the manned exploration and habitation of Mars.[1] An important consideration of such missions is the exposure of crew members to the damaging effects of ionizing radiation from high-energy galactic cosmic ray fluxes and solar proton flares. The crew will encounter the most harmful radiation environment in transit to Mars from which they must be adequately protected. However, once on the planet's surface, the Martian environment should provide a significant amount of protection from free-space radiative fluxes.

In current Mars scenario descriptions, the crew flight time to Mars is estimated to be anywhere from 7 months to over a year each way, with stay times on the surface ranging from 20 days to 2 years.[1] To maintain dose levels below established astronaut limits, dose estimates need to be determined for the entire mission length. With extended crew durations on the surface anticipated, the characterization of the Mars radiation environment is important in assessing all radiation protection requirements. This synopsis[2] focuses on the probable doses incurred by surface inhabitants from the transport of galactic cosmic rays and solar protons through the Mars atmosphere.

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Dose estimates are predicted using the galactic cosmic ray (GCR) flux-energy distribution for the minimum of the solar activity cycle or the time of maximum GCR flux as prescribed by the Naval Research Laboratory CREME model.[3] It is believed that these GCR flux intensities do not vary significantly within the area of the solar system occupied by the terrestrial planets; thus, this model is applied directly to Mars. For the solar flares, the fluence (time-integrated) spectra at 1 A.U. are used for the three largest flares observed in the last half-century, which include the events of August 1972, November 1960, and February 1956.[4] In the vicinity of Mars (approximately 1.5 A.U.), the fluence from these flares is expected to be less; however, there is still much discussion about the dependence of the flare's radial dispersion with distance. Therefore, for the flare calculations in this analysis, the free-space fluence-energy spectra at 1 A.U. have been conservatively applied to Mars.

The Mars atmosphere provides protection from galactic cosmic rays and solar flares with the amount of protection depending on the composition and structure of the atmosphere and the crew member's altitude. In this analysis, the composition of the atmosphere is assumed to be 100% carbon dioxide. The Committee on Space Research has developed warm-high and cool-low density models of the atmosphere structure.[5] The low-density model and the high-density model assume surface pressures of 5.9 and 7.8 mb, respectively. The amount of protection provided by the atmosphere, in the vertical direction, at various altitudes is shown in Table 1. Dose predictions at altitudes up to 12 km are included in the analysis because of the great deal of topographical relief present on the Mars surface.

The NASA Langley Research Center nucleon and heavy-ion transport computer codes are used to predict the propagation and interactions of the free-space nucleons and heavy ions through the Mars atmosphere. For large solar flare radiation, the Baryon Transport code, BRYNTRN,[6] is used. For the galactic cosmic rays, an existing heavy-ion code is integrated with the BRYNTRN code to include the transport of high-energy heavy ions up to atomic number 28.[7,8] Both codes solve the fundamental Boltzmann transport equation in the one-dimensional, or "straight ahead," approximation form:

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S_j(E) + \mu_j(E)\right] \Phi_j(x, E) = \sum_{k>j} \int_E^\infty \sigma_{jk}(E, E') \times \Phi_k(x, E')\, dE'$$

where the quantity to be evaluated $\Phi(x, E)$ is the flux of particles of type j having energy E at spatial location x. The solution methodology of this integro-differential equation may be described as a combined analytical-numerical technique with the accuracy of this numerical method determined to be within 1% of the exact benchmark solutions.[9] The data required for solution consist of the stopping power S_j in various media, the macroscopic total nuclear cross sections μ_j, and the differential nuclear cross sections σ_{jk}. The present code formulation is considered an interim version because some features of the transport interaction phenomena have yet to be incorporated; however, it is believed that the present version does provide a reasonable estimate of cosmic ray propagation fluxes and the corresponding dose predictions.

The absorbed dose due to energy deposition at a given location by all particles can be related to the biological system damage by introducing the quality factor Q, as specified by the International Commission on Radiological Protection.[10] Thus, the dose-equivalent (rem) values H used to specify radi-

Table 1 Mars atmospheric protection in the vertical direction

Altitude, km	Low-density model, g CO_2/cm^2	High-density model, g CO_2/cm^2
0	16	22
4	11	16
8	7	11
12	5	8

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Table 2 Integrated skin dose-equivalents (rem) for the Mars atmosphere models

Integrated dose, rem		Altitude, km 0	4	8	12
Galactic cosmic ray	high-density	11.3	13.4	15.8	18.6
	low-density	13.2	15.9	18.9	22.4
Solar flare event 8/72	high-density	3.9	9.5	21.1	42.8
	low-density	9.0	21.9	46.2	82.6
Solar flare event 11/60	high-density	6.4	10.0	14.8	21.1
	low-density	9.7	15.1	13.3	15.9
Solar flare event 2/56	high-density	9.2	11.1	13.3	15.9
	low-density	11.0	13.4	16.2	19.1

Table 3 Integrated BFO dose-equivalents (rem) for the Mars atmosphere models

Integrated dose, rem		Altitude, km 0	4	8	12
Galactic cosmic ray	high-density	10.5	12.0	13.7	15.6
	low-density	11.9	13.8	15.8	18.0
Solar flare event 8/72	high-density	2.2	4.8	9.5	17.4
	low-density	4.6	9.9	18.5	30.3
Solar flare event 11/60	high-density	5.0	7.5	10.6	14.4
	low-density	7.3	10.8	14.8	19.1
Solar flare event 2/56	high-density	8.5	10.0	11.7	13.4
	low-density	9.9	11.8	13.6	15.3

ation exposure limits are computed as the following:

$$H(x) = \sum_j \int_0^\infty Q_j(E)S_j(E)\Phi_j(x, E)\, \mathrm{d}E$$

Maximum dose-equivalent limits for U.S. astronauts have been recommended by the National Council on Radiation Protection and Measurement (NCRP).[11] For high-energy radiation from galactic cosmic rays and large solar flare ions, the dose delivered to the vital organs, referred to as the blood-forming-organ (BFO) dose, is the most important with regard to latent carcinogenic effects. This is usually computed as the dose incurred at a 5 cm depth in human tissue, simulated in this analysis by 5 cm of water. The 30-day skin and BFO limits for U.S. astronauts are presently 150 and 25 rem, respectively. The annual limits for skin and BFO doses are 300 and 50 rem, respectively. The total career limit for the skin is 600 rem, and the total career BFO dose limit varies between 100 and 400 rem, depending on age and gender.

The surface doses at various altitudes in the atmosphere are determined from the computed propagation data for the GCR and solar flare protons. The dosimetric values at a given target point are computed for carbon dioxide absorber amounts along slant paths in the atmosphere. In these calculations, a spherically concentric atmosphere is assumed. For a given target point, the absorber amounts and the corresponding dosimetric quantities are evaluated for zenith angles between 0 and 90 deg in 5 deg increments. The total doses are then found by numerical integration with respect to the solid angle at the target point.

Integrated dose-equivalent calculations were made for both the high-density and low-density atmosphere models at altitudes of 0, 4, 8, and 12 km. The corresponding skin and BFO dose estimates are shown in Tables 2 and 3. A total yearly skin and BFO dose may be conservatively estimated as the sum of the annual GCR dose and the dose due to one large flare. At an altitude of 0 km, such an estimated skin dose-equivalent is 21–24 rem/yr and an estimated BFO dose-equivalent is 19–22 rem/yr. At an altitude of 12 km, an estimated skin dose-equivalent is 61–105 rem/yr and an estimated BFO dose-equivalent is 33–48 rem/yr. These dose predictions imply that the atmosphere of Mars may provide shielding sufficient to maintain the annual skin and BFO dose levels below the current 300 and 50 rem/yr U.S. astronaut limits. The 30-day limits are important when considering the doses incurred from a solar flare event. The maximum estimated skin dose-equivalent incurred from a flare event is 11 rem at the surface and 83 rem at an altitude of 12 km. These values are well below the current 150 rem astronaut 30-day limit. The maximum estimated BFO dose-equivalent incurred from a flare event is 10 rem at the surface and 30 rem at an altitude of 12 km. The 30-day BFO dose-equivalent is exceeded at an altitude of 12 km. However, as seen in Table 3, the August 1972 flare is rapidly attenuated by matter, and a few g/cm^2 of additional shielding should reduce the anticipated dose below this limit. These dose predictions imply that the atmosphere of Mars may also provide significant shielding to help maintain 30-day dose levels within permissible astronaut limits.

The aforementioned calculated doses are for humans on the surface of Mars with their only protection being the carbon dioxide atmosphere. Additional protection will be provided by the crew's habitat structure, equipment, and consumables. The atmosphere is predicted to provide sufficient shielding to maintain incurred doses below NCRP-established limits if the astronauts are not at high altitudes of ~12 km and if large doses have not already been received by the astronauts. It must be realized that Mars exploration crews are likely to incur a substantial dose while in transit to Mars, perhaps from other radiation sources (e.g., nuclear reactors), that will reduce the allowable dose that can be received while on the surface. In this case, it may become necessary to provide additional shielding, perhaps in the form of a solar flare shelter or by utilizing local resources such as Martian regolith.

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