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Extreme solar event of AD775: Potential radiation exposure to crews in deep space

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ABSTRACT

The existence of a historically large cosmic event in AD774 or 775, of probable solar origin, has recently been confirmed from records of ^{14}C levels in tree rings located at widely separated locations on Earth, ^{10}Be records in polar ice cores, and historical records of aurora sightings. Usoskin et al. (2013) [16] suggest that such an event, of solar origin, would have a proton fluence of $\sim 4.5 \times 10^{10}$ cm^{-2} at energies above 30 MeV, with a hard energy spectrum comparable to the event of 23 February 1956. In this work we investigate the possible radiation exposures to crews of missions on the surface of Mars, from such an event. In this work we use the HZETRN radiation transport code, originally developed at NASA Langley Research Center, and the Computerized Anatomical Male and Female human geometry models to estimate exposures for a variety of aluminum shield areal densities similar to those provided by a spacesuit, surface lander, and permanent habitat on the Martian surface. Comparisons of the predicted organ exposures with recently-recommended radiation exposure limits are made. Potential health effects on crews, of such an event, are also discussed.

1. Introduction

Human missions to Mars will involve chronic exposures to the ever-present galactic cosmic ray (GCR) background, as well as possible exposures to dangerous solar particle events (SPEs). The highest exposures from the background GCR environment is likely to occur during the transit and surface stays associated with a Mars mission. Although particle energies from GCR particles can be as high as 10^{20} eV, exposures from them do not present an acute radiation hazard, as they are too low to cause an acute radiation syndrome response. Annual doses from the GCR environment are likely to be 200 mGy or less [1,2]. Instead, the primary health concern from the GCR environment is stochastic effects, such as cancer induction and mortality, or possible neurological effects [3,4]. Because of their extremely energetic spectra, the GCR environment is difficult to shield. Exposures from SPEs, however, are more complicated to accurately estimate due to the large variability in particle intensities and energy distributions, and the effects of shielding on the estimated exposures. The highest exposures from these events will likely occur during transits when the only shielding available is intrinsic to the spacecraft itself. On the surface of Mars, half of the incident environment is shielded by the planet's bulk. For surface operations on Mars, the thin, overlying atmosphere also provides added radiation protection. Hence, accounting for the crew's space suits, surface landers, or habitats, exposures from SPEs on planetary surfaces may be significantly lower than those received during lengthy transits in deep space [1,5,6].

Recent studies [5–14] focused on estimating crew radiation exposures on the Martian surface near the mean elevation datum for a variety of galactic cosmic ray (GCR) and solar particle event scenarios. Results from two of these studies [5,8] suggest that crews near the mean surface elevation on Mars are unlikely to receive exposures from GCR particles that exceed recently-recommended space radiation limits [15]. Results from studies of exposures to energetic solar particle events (SPEs) show a large variability depending upon the assumed spectrum intensity. One study, using three events that were among the largest of the spacefaring era (August 1972, September 1989 and October 1989) found that exposures from those events would not have exceeded radiation limits for operations at the mean surface elevation of Mars [6].

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It is certainly plausible to expect that larger events than those observed during the current spacefaring era may have occurred. Data from ice core samples obtained from the polar regions of Earth and excessive ^{14}C production worldwide in tree rings suggests that much larger events may have occurred within the past ~1200 years [16]. Due to this possibility, analyses [11–14] of potential SPE exposures on the surface of Mars were performed for a variety of assumed Carrington-class events. These assumed spectra were normalized to a greater than 30 MeV omni-directional proton fluence level of 18.8×10^9 cm^{-2} estimated from an analysis of ice core data of the September 1859 Carrington event reported in Ref. [17]. Although the scientific record is clear that the Carrington event did occur in September 1859, present consensus within the scientific community is that the ice core data cannot be used to extract information about proton intensities for this event since the evidence for such a proton event cannot be confirmed from other ice cores [18].

The existence of a historically large cosmic event in AD774 or 775, of probable solar origin, has recently been confirmed from records of ^{14}C levels in tree rings located at widely separated locations on Earth, ^{10}Be records in polar ice cores, and historical records of aurora sightings [16]. The authors suggest that such an event would have a proton fluence of $\sim 4.5 \times 10^{10}$ cm^{-2} at energies above 30 MeV, with a hard energy spectrum comparable to the event of 23 February 1956. Therefore, based upon the findings in Ref. [16], we have chosen to use the Band fit spectral shape for the actual February 1956 event for the present analysis of this extreme event. Assuming harder event spectra would result in increased exposures over those presented herein. Softer event spectra would result in lower exposures.

Section 2 outlines the assumed scenarios. This is followed by Section 3, which presents a description of the computational methods used to obtain crew organ doses and effective doses. Section 4 presents the results of the exposure calculations. Finally, Section 5 summarizes this work and presents concluding remarks.

2. Surface scenarios

As was done in previous studies [7,14], we assume for simplicity that the crew member (male or female) is located at ground level in the center of an aluminum hemispherical structure on the surface of Mars. This simple geometry, compared to more realistic geometries, permits reasonable estimates of the upper bounds of exposures for a given nominal shield thickness [19]. As was assumed in earlier Mars surface studies [2–4], three areal densities for the aluminum hemisphere are used corresponding to a spacesuit (0.3 g cm^{-2}), surface lander (5 g cm^{-2}), and a surface habitat (40 g cm^{-2}). Only small differences in dose estimates are expected with aluminum ($Z=13$, $A=27$) shielding rather than Mars regolith since the average composition of Mars regolith ($Z_{ave}=14.86$ and $A_{ave}=30$) is similar. The hemispheres are located at elevations ranging from the summit of Olympus Mons (25 km above the mean surface elevation) to the depths of the Hellas Impact Basin (7 km below the mean surface elevation). The Mars atmosphere is assumed to be composed of pure CO_2 and is modeled using the NASA Mars Atmosphere Model based upon data from the 1996 Mars Global Surveyor mission [20].

The incoming SPE protons have an isotropic distribution. Therefore, the atmosphere path lengths traversed by them are longer for those particles arriving at angles greater than zero, with respect to the local zenith. This is accounted for in the calculations by averaging the exposures in one degree increments for all arrival angles from the zenith to the horizon. Near the horizon, the areal densities increase significantly (~300 g cm^{-2}), especially for locations deep in the atmosphere. Surface curvature effects are accounted for in determining the atmosphere path lengths. Table 1 displays atmosphere thicknesses (areal densities) in the zenith direction versus altitude obtained from the model in Ref. [20].

Table 1
Mars atmosphere thickness, in units of areal density (g cm^{-2}), at the local zenith, as a function of altitude (km) relative to the mean surface elevation.

Altitude (km)	Atmosphere thickness (g cm^{-2})
25	2.2
20	3.3
15	4.8
10	7.2
7	9.2
0	16.7
−4	23.5
−7	30.5

3. Computational methods

The Band function parameterization utilizes high energy data obtained from ground level enhancements (GLEs) measured by neutron monitors on Earth's surface. Thus, it should yield better dose estimates than other, less accurate parameterizations, such as a simple single exponential in rigidity fit [21,22]. The Band function parameterization of the February 1956 event proton distribution [22] is given by Eq. (1), where $\Phi(>R)$ is the proton fluence, $\Lambda=4.5\times10^{10}$ protons cm^{-2} is the normalization constant re-normalized to the AD775 event fluence reported by Usoskin et al. [16], R is the particle rigidity (momentum per unit charge) in units of GV (gigavolts), $R_0=0.321$ GV is the characteristic rigidity, and $\gamma_1=0.584$ and $\gamma_2=5.04$ are spectral indices.

$$\Phi(>R) = \begin{cases} \Lambda R^{-\gamma_1} \exp\left(-\dfrac{R}{R_0}\right), & \text{for } R \le (\gamma_2-\gamma_1)R_0 \\ \Lambda R^{-\gamma_2}\left[(\gamma_2-\gamma_1)R_0\right]^{(\gamma_2-\gamma_1)} \exp(\gamma_1-\gamma_2), & \text{for } R \ge (\gamma_2-\gamma_1)R_0 \end{cases} \tag{1}$$

Fig. 1 displays the assumed AD775 spectrum compared to the Band function fit for the actual February 1956 solar particle event.

This incident AD775 SPE proton spectrum is transported in

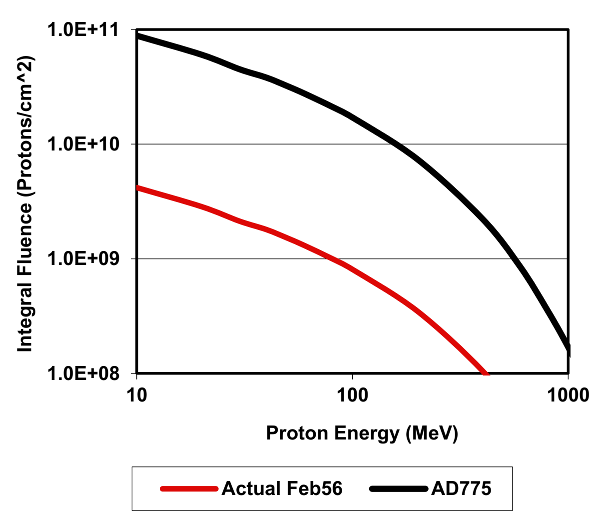

Fig. 1. Solar proton integral spectra for the actual February 1956 solar particle event and renormalized to the AD775 event fluence level.