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ARTICLE

Estimates of extreme solar particle event radiation exposures on Mars

Lawrence W. Townsend*, Anne M. Adamczyk, Charles M. Werneth, Hanna M. Moussa and Jeremy P. Townsend

The University of Tennessee, Knoxville, Tennessee, 37996-2300 USA

Estimates of effective doses and organ doses for male and female crew members are made for solar particle event proton environments comparable to several of the most significant solar particle events, which occurred in the second half of the 19th century (1864, 1878, 1894, 1895, and 1896). The incident proton energy distributions for these solar particle events are assumed to be similar to that of the November 1960 event, one of the most energetic of the modern space era. The crewmembers are assumed to be located at the mean surface elevation on Mars, at the lowest elevation on Mars in the Hellas Impact Basin, and on the summit of Olympus Mons, the highest surface elevation on Mars. The crewmembers are assumed to be shielded by the overlying carbon dioxide atmosphere of Mars, and locally shielded by a space suit, a surface landing spacecraft, or a surface habitat. These estimates are compared with current NASA Permissible Exposure Limits.

Keywords: space radiation exposure; solar particle event; Mars; crew doses

1. Introduction

Future missions to Mars may include human crews who might be exposed to potentially lethal or mission threatening solar particle events (SPEs). Thus, estimating exposures to plausible worst case events is important for evaluating shield requirements needed to protect human crews. Hypothetical worst case SPEs were previously evaluated [1-2] using fluences based on the nitrate concentration in ice core samples [3]. Recently, the validity of these ice core results has been called into question [4]. Others, however, have defended their validity [5]. Resolution of this issue remains to be decided. Nevertheless, in this work, the fluence of protons for the next five largest possible events (1864, 1878, 1894, 1895, and 1896) in the ice core data, since 1859 and prior to the modern era of space exploration (1950's), will be used in combination with the proton energy spectrum from the November 1960 SPE, which is one of the largest events of the modern space era.

2. Computational methods

In this work, organ doses and effective doses, relevant for comparisons to the NASA permissible exposure limits (PELs) are calculated using NASA's On-Line Tool for the Assessment of Radiation in Space (OLTARIS) [6] for three possible Martian surface scenarios: a space suit (0.3 g cm^{-2} aluminum areal density), a surface landing spacecraft (5 g cm^{-2} aluminum areal density), or a surface habitat (40 g cm^{-2} aluminum areal density.

2.1. Incident SPE spectra

The modeled incident spectrum uses a Band function fit to the November 1960 SPE renormalized to the >30 MeV proton fluences from the ice core analyses for each event. These fluence values are displayed in **Table 1**.

Table 1. Integral fluences for the five events. Also displayed are the integral fluence values, J_0, for each event.

Event Year	>30 MeV Fluence (protons cm^{-2})	J_0 (protons cm^{-2})
1864	7.00×10^9	6.39×10^9
1878	5.00×10^9	4.57×10^9
1894	7.70×10^9	7.03×10^9
1895	1.11×10^{10}	1.01×10^{10}
1896	8.00×10^9	7.31×10^9

The Band function parameterization is given by [7]

$$\Phi(>R)=\begin{cases} J_0 R^{-\gamma_1}\exp\left(-\frac{R}{R_0}\right) & for\ R\le(\gamma_2-\gamma_1)R_0 \\ J_0 R^{-\gamma_2}\left[(\gamma_2-\gamma_1)R_0\right]^{(\gamma_2-\gamma_1)}\exp(\gamma_1-\gamma_2) & \\ & for > R(\gamma_2-\gamma_1)R_0 \end{cases} \tag{1}$$

Here, Φ is the proton fluence, J_0 is the total integral proton fluence, R is the particle rigidity (momentum per unit charge), R_0 = 0.321 GV is the characteristic rigidity,

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*Corresponding author. Email: ltownsen@tennessee.edu and $\gamma_1 = 0.584$ and $\gamma_2 = 5.04$ are spectral indices. Values for J_0 are listed in Table 1.

2.2. Particle transport

Transport methods used in OLTARIS are based on HZETRN2010 [8], the latest version of the deterministic space radiation transport code developed at NASA Langley Research Center. In this work, HZETRN models the transport of all incident charged protons and their nuclear reaction products (protons, neutrons, deuterons, tritons, helions, and alpha particles). The database of secondary nuclear reaction products for HZETRN2010 is provided by the nuclear fragmentation model NUCFRG3 [9]. In this application, the particles are transported through 300 g cm^{-2} of Mars' carbon dioxide atmosphere, followed by transport through the appropriate aluminum shielding (0.3, 5 or 40 g cm^{-2}), and then transport through human tissue. The resulting doses are folded with the computerized anatomical male (CAM) and computerized anatomical female (CAF) models [10-11] to estimate organ doses and effective doses.

2.3. Radiation exposure quantities and limits

2.3.1 Organ doses and limits

Table 2. NASA PELs for short term or career non-cancer effects. N/A means not applicable.

Organ	30 day Limit (cGy-Eq)	1 year Limit (cGy-Eq)	Career Limit (cGy-Eq)
Lens	100	200	400
Skin	150	300	400
BFO	25	50	N/A
Heart	25	50	100
CNS	50	100	150

NASA radiation limits for short term (acute) radiation exposures are presented in **Table 2**, which lists permissible exposure limits (PELs) for thirty days, one year, and career for non-cancer radiation effects [12]. Organs considered are the eye lens, skin, blood forming organs (BFO), heart, and central nervous system (CNS). For comparison to the PELs, organ doses are converted from units of centigray (cGy) to units of centigray-equivalent (cGy-Eq) using a Relative Biological Effectiveness (RBE) factor as specified in Ref. [13]. This is accomplished using Eq. (2) where, for protons, RBE = 1.5.

$$D[cGy-Eq] = D[cGy] \times RBE \tag{2}$$

2.3.2 Effective dose and limits

Effective dose (E), in units of centiSievert (cSv), is calculated using

$$E = \sum_T w_T H_T , \tag{3}$$

where w_T is the tissue weighting factor obtained from Ref. [15]. The organ dose equivalent H_T, in Eq. (3), is in units of cSv and is calculated in OLTARIS from the product of the radiation quality factor, Q [14] and organ dose, D. NASA's career effective dose limits [13], shown below in **Table 3**, are established to reduce the probability of developing a fatal cancer to 3% with 95% confidence.

Table 3. Career exposure limits as a function of age at first exposure for a mission not exceeding one year in duration.

Age (years)	Effective Dose (cSv)	
	Male	Female
25	52	37
30	62	47
35	72	55
40	80	62
45	95	75
50	115	92
55	147	112

2.4. Radiation exposure scenarios

Organ doses and effective doses, for male (CAM) and female (CAF) crew members shielded by a space suit, a surface landing spacecraft, and a surface habitat are calculated for locations at the top of Olympus Mons (+25 km altitude – the highest point on Mars, 2.2 g cm^{-2} CO_2), the mean surface elevation datum (0 km altitude, 16.7 g cm^{-2} CO_2), and in the Hellas Impact Basin (-7 km altitude – the lowest point on Mars, 30.5 g cm^{-2} CO_2). For each location, incident SPE protons arrive from all angles between 0 and 90 degrees with respect to the local zenith and are averaged over all particle arrival path length areal densities.

3. Organ dose and effective dose results

Organ doses and effective doses are presented below in **Tables 4 - 9**. In Tables 4 - 8 organ doses that exceed the PELs are indicated in bold. It is clear that nearly all organ doses at the summit of Olympus Mons, shielded only by a space suit, exceed dose limits. Also, BFO, CNS and heart dose limits may be exceeded for some events within a lander located at the summit. No limits are exceeded within a habitat or for any shield configuration at or lower than the mean surface elevation. From Table 9, effective dose limits are exceeded for males under the age of 45 and females under the age of 50 shielded by only a space suit.

4. Concluding remarks

Radiation exposures on Mars for a variety of hypothetical, large SPEs have been presented. In nearly all scenarios, only thinly-shielded crews on the summit of Olympus Mons appear to exceed exposure limits. As expected, the 1895 event, which had the highest proton fluence, yielded the largest exposures.

Table 4. Skin dose as a function of event, altitude, and aluminum shielding for male (CAM) and female (CAF) crew members. Skin doses for the 1878 event are all below the PELs and are not shown.

Skin Dose (cGy-Eq)										
Event Year	Human Body Model	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
		Elevation			Elevation			Elevation		
		+25 km	0 km	-7 km	+25 km	0 km	-7 km	+25 km	0 km	-7 km
1864	CAM	**154**	11	4	70	9	4	10	3	2
	CAF	**153**	11	4	70	9	4	10	3	2
1894	CAM	**158**	12	5	72	9	4	10	3	2
	CAF	**157**	12	5	72	9	4	10	4	2
1895	CAM	**244**	18	7	111	14	6	16	5	3
	CAF	**243**	18	7	111	15	6	16	5	3
1896	CAM	**176**	13	5	80	10	4	12	4	2
	CAF	**175**	13	5	80	11	4	12	4	2

Table 5. Eye lens dose as a function of event, altitude, and aluminum shielding for male (CAM) and female (CAF) crew member. Eye lens doses for the 1878 event are all below the PELs and are not shown.

Eye Lens Dose (cGy-Eq)										
Event Year	Human Body Model	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
		Elevation			Elevation			Elevation		
		+25 km	0 km	-7 km	+25 km	0 km	-7 km	+25 km	0 km	-7 km
1864	CAM	**101**	11	4	58	9	4	10	3	2
	CAF	**102**	10	4	59	9	4	10	4	2
1894	CAM	**103**	11	5	59	9	4	10	4	2
	CAF	**105**	10	5	60	9	4	10	4	2
1895	CAM	**159**	17	7	91	14	6	16	5	3
	CAF	**162**	16	7	93	14	6	16	6	3
1896	CAM	**115**	12	5	66	10	4	12	4	2
	CAF	**117**	11	5	67	10	4	12	4	2

Table 6. BFO dose as a function of event, altitude, and aluminum shielding for male (CAM) and female (CAF) crew members.

Blood Forming Organ Dose (cGy-Eq)										
Event Year	Human Body Model	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
		Elevation			Elevation			Elevation		
		+25 km	0 km	-7 km	+25 km	0 km	-7 km	+25 km	0 km	-7 km
1864	CAM	**47**	8	4	**33**	7	3	8	3	2
	CAF	**50**	7	4	**34**	7	3	8	3	2
1878	CAM	**34**	6	3	24	5	2	6	2	1
	CAF	**36**	5	3	25	5	2	6	2	1
1894	CAM	**49**	8	4	**34**	7	3	8	3	2
	CAF	**51**	8	4	**35**	7	3	8	3	2
1895	CAM	**75**	12	6	**52**	11	5	12	5	3
	CAF	**79**	12	6	**54**	11	5	13	5	3
1896	CAM	**54**	9	4	**38**	8	4	9	3	2
	CAF	**57**	8	4	**39**	8	4	9	3	2

Table 7. CNS dose as a function of event, altitude, and aluminum shielding for male (CAM) and female (CAF) crew members. CNS doses for the 1878 event are all below the PELs and are not shown.

CNS Dose (cGy-Eq)										
Event Year	Human Body Model	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
		Elevation			Elevation			Elevation		
		+25 km	0 km	-7 km	+25 km	0 km	-7 km	+25 km	0 km	-7 km
1864	CAM	50	9	4	36	7	3	9	3	2
	CAF	**54**	9	4	38	8	4	9	3	2
1894	CAM	**51**	9	4	37	8	4	9	3	2
	CAF	**55**	9	4	39	8	4	9	3	2
1895	CAM	**79**	14	6	**57**	12	5	13	5	3
	CAF	**85**	14	6	**60**	12	6	14	5	3
1896	CAM	**57**	10	4	41	8	4	10	4	2
	CAF	**61**	10	4	44	9	4	10	4	2

Table 8. Heart dose as a function of event, altitude, and aluminum shielding for male (CAM) and female (CAF) crew members.

Heart Dose (cGy-Eq)										
Event Year	Human Body Model	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
		Elevation			Elevation			Elevation		
		+25 km	0 km	-7 km	+25 km	0 km	-7 km	+25 km	0 km	-7 km
1864	CAM	**36**	7	3	**27**	6	3	7	3	2
	CAF	**38**	7	3	**28**	6	3	7	3	2
1878	CAM	**26**	5	2	19	4	2	5	2	1
	CAF	**27**	5	2	20	5	2	5	2	1
1894	CAM	**37**	7	3	**28**	6	3	7	3	2
	CAF	**39**	8	3	**29**	7	3	8	3	2
1895	CAM	**57**	11	5	**43**	10	5	11	4	3
	CAF	**60**	12	5	**45**	10	5	12	4	3
1896	CAM	**41**	8	4	**31**	7	3	8	3	2
	CAF	**43**	8	4	**32**	7	3	8	3	2

Table 9. Effective dose as a function of event, altitude, and aluminum shielding for male (CAM) and female (CAF) crew members.

Effective Dose (cSv)										
Event Year	Human Body Model	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
		Elevation			Elevation			Elevation		
		+25 km	0 km	-7 km	+25 km	0 km	-7 km	+25 km	0 km	-7 km
1864	CAM	52	10	5	35	9	5	10	5	3
	CAF	49	10	5	34	9	5	10	5	3
1878	CAM	37	7	4	25	6	3	7	3	2
	CAF	35	7	4	25	6	3	7	3	2
1894	CAM	54	10	5	36	9	5	11	5	3
	CAF	51	10	5	35	9	5	11	5	3
1895	CAM	83	15	8	56	14	7	17	8	5
	CAF	78	15	8	55	14	8	17	8	5
1896	CAM	60	11	6	40	10	5	12	6	4
	CAF	56	11	6	39	10	5	12	5	4

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