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The Carrington event: Possible doses to crews in space from a comparable event

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Abstract

Recent ice core analyses suggest that the Carrington event of 1859 may have been the largest solar energetic particle event in the past several hundred years. Previous analyses of potential doses to humans and electronics from such an event suggested that a Carrington-like event, with a hard spectrum similar to that of the event of September 1989 could be catastrophic. Subsequent analyses of the ^{10}Be concentration in the ice core data suggest that the spectral hardness of the Carrington event was softer and similar to the August 1972 event. In this work we review the earlier estimates of doses from a Carrington event, and present updated dose estimates for deep space crews and electronics using the Carrington event proton fluence $\geqslant 30$ MeV in combination with an event spectrum similar to that of the August 1972 event. Potential ramifications of these doses for humans and electronics on deep space missions are discussed.

Keywords: Solar energetic particle event; Space radiation; Total ionizing doses; Carrington Flare; Space radiation risks

1. Introduction

During the space era many solar energetic particle events (SPEs) have been observed. Most have too few energetic protons to be a health concern to interplanetary crews. Extremely large events can, however, pose significant health risks to crews, especially if adequate shielding is not provided. These events typically occur only once or twice during an 11-year solar cycle. An unresolved issue in the space radiation protection community is "What constitutes a worst case event?" For mission planning purposes a realistic, hypothetical worst-case solar particle event spectrum can provide a reasonable upper bound on radiation doses for these sporadic events.

In previous work, estimates of interplanetary crew organ doses for several plausible worst-case solar particle events have been made and the results summarized elsewhere (Townsend et al., 2001). These analyses typically involved various combinations of events, or arbitrary scaling of measurements of large events, that previously occurred during the four decades of the space era. Recently, we took a different approach and investigated plausible worst-case SPE spectra based on recently reported SPE fluence estimates obtained from the concentration of nitrates found in ice core samples spanning approximately the last 500 years (McCracken et al., 2001). Details of the methodology are available in McCracken et al. (2001) and references therein. For this 500 year period the "Carrington" solar flare of 1859 had

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the largest estimated integral fluence of protons >30 MeV with a value of 18.8×10^9 cm^{-2}. This value was at the top of the polar atmosphere (exoatmospheric) and is assumed to be that which would have been found in space at the location of Earth's orbit. Hence, it may be an excellent candidate for a plausible worst-case event. Unfortunately, one fluence datum at a single energy does not constitute a spectrum. Hence, to generate plausible spectra, the Carrington flare fluence for >30 MeV protons, reported by McCracken et al. (2001) has been used as an overall normalization in combination with the spectral shapes of several large solar particle events from the space era to create hypothetical worst-case solar particle event spectra, which have been used to assess possible doses in electronics (Townsend et al., 2003) and humans (Stephens et al., 2005; Townsend et al., 2004).

In this work, we summarize our earlier work on hypothetical doses from the Carrington event, and present revised estimates of critical organ doses based upon more recent analyses of the Carrington event spectrum.

2. Previous analyses of organ doses

Analyses of possible doses from a solar energetic particle event similar to the Carrington Event of 1859 have been carried out for purposes of estimating doses in deep space for electronics (Townsend et al., 2003) and humans (Stephens et al., 2005); and for humans in low-Earth orbit (Townsend et al., 2004). In these analyses various spectral shapes were assumed. All were normalized to the Carrington event >30 MeV proton fluence value of 1.88×10^{10} cm^{-2} reported in McCracken et al. (2001). The findings of each of these analyses are summarized in the following sections.

2.1. Organ doses in LEO

To generate plausible spectra, the Carrington event fluence of >30 MeV protons was used as an overall normalization point in combination with the measured spectral shapes of two, recent large solar particle events from the space era, the events of September 1989 and March 1991, to create hypothetical worst-case solar particle event spectra (Townsend et al., 2004). The question addressed in that study was, "How large a problem could an event of this magnitude be for missions in LEO where there is some protection afforded by the Earth's geomagnetic field and actual physical bulk?" To answer this question, doses to the skin, ocular lens, and bone marrow were estimated, as a function of aluminum shield thickness, for the two assumed spectra using the BRYNTRN space radiation transport code developed at NASA Langley Research Center (Wilson et al., 1991). BRYNTRN transports SPE protons and their reaction products (protons, neutrons, deuterons, tritons, hellions, and alphas) through the aluminum shield material and body tissues overlying the critical organs of interest. Distributions of the body organ self-shielding are obtained with the Computerized Anatomical Man (CAM) model (Billings and Yucker, 1973), which is the standard human geometry model used within NASA to estimate organ doses. The input spectra were assumed to be represented by an energy (Weibull) parameterization form based upon the fits for the September 1989 and March 1991 events by Xapsos et al. (2000)

$$\frac{d\Phi}{dE} = \Phi_0 k \alpha E^{\alpha-1} \exp(-kE^{\alpha}), \tag{1}$$

where Φ is the proton fluence, E is the proton energy in MeV, and Φ_0, k and α are parameters used to fit the spectra. They are listed in Table 1.

The incident SPE proton spectra are altered by the presence of the Earth's magnetic field, which is dipole-like in configuration. Charged particles that arrive at some point within the geomagnetosphere are deflected by the Lorentz force. For some energies and trajectories the incident protons are deflected back into space and are unable to penetrate to the location of the spacecraft. In that work, we used the geomagnetic cutoff model developed at NASA Langley Research Center (Wilson et al., 1990). The solid mass of the Earth also provides protection by cutting off particle trajectories that pass through it. Hence, the incident spectra are reduced by the Earth's shadow shielding. We also assumed for simplicity that the spacecraft orbits were circular and that the spacecraft was always in the most exposed orbit. The latter is a crude approximation since it results in significant overestimates of the actual organ doses. Nevertheless, the lack of knowledge of the actual fluence versus time development of the Carrington event precludes any reasonable attempt to include orbital phasing and thereby obtain realistic estimates. Finally, geomagnetic storm effects on the magnetic field cutoffs were also modeled using the Langley model (Wilson et al., 1990).

Organ doses using the two assumed spectra were calculated for orbit inclinations from 28.5° to 90° at a 400 km altitude. Typical results, taken from Townsend

Table 1
Spectral parameters for hypothetical Carrington event spectra in power law parameterization form

Spectrum shape used	Φ_0 (protons cm^{-2})	k	α
August 1972	5.23×10^{10}	0.0236	1.108
August 1989	1.81×10^{12}	1.166	0.4015
September 1989	4.79×10^{11}	0.877	0.3841
October 1989	4.64×10^{12}	2.115	0.2815
March 1991	1.47×10^{12}	0.972	0.441

Parameters for five spectral shapes from events in the space era are displayed. All are normalized to the >30 MeV proton fluence value of McCracken et al. (2001).

Table 2
Organ doses in a 400 km – 51.6° orbit as a function of aluminum shield thickness for hypothetical Carrington event spectra (Townsend et al., 2004)

Aluminum shield (g cm^{-2})	Skin dose (cGy)		Eye dose (cGy)		Bone marrow dose (cGy)	
	September 1989 spectrum	March 1991 spectrum	September 1989 spectrum	March 1991 spectrum	September 1989 spectrum	March 1991 spectrum
1	944	1197	625	666	76.8	29.8
2	483	455	376	308	66.6	23.2
5	180	102	163	84.9	47.0	12.6
10	77.1	26.7	74.6	24.5	30.1	5.9
20	29.1	5.5	29.2	5.4	15.7	2.0
50	6.0	0.45	6.1	0.46	4.3	0.27
100	3.3	0.22	3.4	0.22	2.4	0.13
250	0.69	0.04	0.71	0.04	0.55	0.03

et al. (2004) are displayed in Table 2 for a 51.6° orbit, similar to that of the International Space Station. Note that the organ doses are quite large [up to ~12 Gy (~1200 rads) for the skin and up to ~80 cGy (80 rads) to the bone marrow] and could present a health risk to crews who are not adequately protected. To reduce the doses from an event of this magnitude below the appropriate limits recommended by the National Council on Radiation Protection and Measurements (NCRP, 2000) requires ~18 g cm^{-2} aluminum shielding. As pointed out earlier, however, these estimates are for a spacecraft confined to the most exposed orbit and probably represent significant overestimates of the actual dose that would be received if such an event were to occur. They do, however, provide a reasonable upper bound for on possible organ doses. Details of the models used and the complete set of organ doses calculated are presented in Townsend et al. (2004).

2.2. Organ doses in deep space

For this study, five worst case spectra were assumed based upon the spectra for the 4 August 1972, 12 August 1989, 29 September 1989, 19 October 1989 and 23 March 1991 events, all normalized to the Carrington event >30 MeV proton fluence value of 1.88×10^{10} cm^{-2}. Parameters for the assumed spectra, represented by a Weibull parameterization (Eq. (1)), are listed in Table 1. These spectra were again transported through spacecraft aluminum shielding and then through body tissues overlying the critical organs of interest using the BRYNTRN space radiation transport code. Again, the CAM model was used to provide the body organ self-shielding distributions. Results of these analyses, excerpted from Stephens et al. (2005), are displayed in Table 3 for the skin, ocular lens of the eye, and the bone marrow.

From these organ dose estimates, it is generally clear that that the largest organ doses result from an assumed spectral shape similar to that of the September 1989 event. This is not surprising since that spectrum is the hardest. The lowest skin and bone marrow doses vary among the August 1972, August 1989 and March 1991 event spectra depending upon the assumed shield thickness. Organ doses for a spectral shape similar to the October 1989 are slightly smaller than those obtained for the September 1989 spectrum shape. This also is not unexpected since the October 1989 event was nearly as hard as the September 1989 event.

In order to compare these dose estimates to the organ doses necessary to induce acute radiation syndrome responses in the crew, which are based upon acute exposures to gammas and not protons, a multiplicative relative biological effectiveness (RBE) factor should be applied (NCRP, 2000). The resulting dose in units of gray-equivalent (Gy-Eq) is obtained from

$$\text{dose(Gy-Eq)} = \text{dose(Gy)} \times \text{RBE}, \qquad (2)$$

where an RBE = 1.5 is assumed, as recommended by the NCRP. Thus, “dose” in units of Gy-Eq, indicates that

Table 3
Organ doses in cGy for crews in deep space from hypothetical Carrington events assuming various spectral shapes from the space era

Aluminum shield thickness	August 1972		August 1989		September 1989		October 1989		March 1991	
	Skin (cGy)	BFO (cGy)	Skin (cGy)	BFO (cGy)	Skin (cGy)	BFO (cGy)	Skin (cGy)	BFO (cGy)	Skin (cGy)	BFO (cGy)
1	3426	141	4362	129	3539	281	3967	212	4480	109
2	1905	105	1710	102	1801	244	1749	180	1694	85
5	556	47	414	59	665	171	546	122	378	46
10	123	15	119	30	282	109	208	75	98	22

Dose results are presented only for the skin and bone marrow (BFO). Doses to the ocular lens are similar to the skin doses. Aluminum shield thicknesses are given in areal density units of g cm^{-2}. These results are excerpted from Stephens et al. (2005).

the absorbed dose (in Gy) has been multiplied by the RBE using Eq. (2).

In Stephens et al. (2005), it was assumed that the whole body dose could be approximated by the bone marrow (BFO) dose. The study showed that significant acute radiation syndrome effects were possible. Behind 1 g cm^{-2} aluminum shielding (slightly thicker than a space suit) an event whose spectrum was very hard (September 1989-like) yielded a dose of 2.8 Gy (4.2 Gy-Eq), which is severe and could result in death. At typical spacecraft shielding thicknesses (5–10 g cm^{-2} aluminum) a BFO dose in the range of 1.6–2.6 Gy-Eq was calculated. Expected symptoms include nausea and emesis, malaise, hematologic damage, and possibly death (NCRP, 2000). To reduce the BFO dose lower than the 0.25 Gy-Eq level (current 30d limit for missions in low-Earth orbit) a 'storm shelter' of 45–50 g cm^{-2} (about 18 cm) of aluminum would be required. From the table, skin doses for space suit shielding (1 g cm^{-2}) for an event of this type could be as large as 56.2 Gy (84.3 Gy-Eq). For the eye (not shown in Table 3) doses could be as large as 26.3 Gy (39.5 Gy-Eq). Possible symptoms include lens cataracts, keratitis, erythema, epilation and moist desquamation (NCRP, 2000). For typical space craft shielding thicknesses (~10 g cm^{-2}) the calculated doses are 2.8 Gy (4.2 Gy-Eq) for the skin and 2.7 Gy (4.1 Gy-Eq) for the eye. The doses are reduced to 0.33 Gy-Eq for both organs behind a storm shelter thickness of 50 g cm^{-2} of aluminum. Such doses would be below the 30d limits for crews on missions in low-Earth orbit currently recommended by the NCRP (2000). Fortunately, the spectrum for the Carrington event appears to be softer (Smart et al., 2005). Hence, the organ doses would be lower and their effects on the crew less severe.

3. Previous analyses of electronic doses in deep space

Since many electronic components are less shielded than the crew quarters, total ionizing doses received in deep space by electronic components from a Carrington-type event could be substantially larger than those received by humans. Such doses might result in component failure, especially for many commercial off the shelf (COTS) parts, which have not been radiation-hardened. In Townsend et al. (2003), doses in silicon materials shielded by aluminum shield thicknesses comparable to those found in manned and unmanned spacecraft were calculated for deep space. The values obtained indicated that a Carrington-type event could present a significant hazard to onboard electronics.

Doses in silicon were calculated for two assumed worst-case events using the BRYNTRN space radiation transport code for five thicknesses of aluminum shielding in free space. These events used the September 1989 and March 1991 spectral shapes. The Carrington event proton spectra were parameterized in Eq. (1) and used the parameter values presented in Table 1. The areal densities for the assumed shielding were 0.1, 0.3, 0.5, 1 and 5 g cm^{-2} Al. They were chosen as being representative of nominal shielding thicknesses for manned and unmanned spacecraft components. Behind the Al shielding is a Si layer whose areal density is assumed to be 0.1 g cm^{-2}. Incident SPE alpha and heavy ion fluxes are not included in these analyses, nor in any of the analyses presented earlier for human exposures, since there are no data for these particle types for the Carrington Flare. Neglect of these components, however, may indicate that the dose estimates presented herein and in our earlier works may be underestimates of the actual doses to be expected from such an event, especially for the very thin shields where the ranges of the alphas and heavy ions are substantially larger than the shield thickness.

Estimates of doses in Si for these two assumed spectra are shown in Table 4. At 0.1 g cm^{-2} (~15 mils), the Carrington March 1991 Spectrum predicted dose value of 54 krad (Si) exceeds the 100% confidence level worst case value of 39 krad (Si) presented ii Xapsos et al. (2000). For 0.5 g cm^{-2} (~73 mils), the March 1991 predicted dose value presented herein exceeds the 100% confidence level worst case value, also presented in Xapsos et al. (2000), by nearly a factor of 2. The predicted dose value of 10.2 krad for the Carrington September 1989 spectrum behind 0.5 g cm^{-2} (~73 mils) Al, however, is very close to the Xapsos et al. (2000) value of 9 krad (Si). These differences, however, may not be significant since the spectra used herein are composed of an assumed spectral shape with a fluence magnitude obtained from the ice core data. Note also that 15 mils is probably much less shielding than any component would have on a modern spacecraft. Nevertheless, total ionizing doses (TID) ~50 krad(Si) from an event such as described herein can be catastrophic for onboard electronics for both manned and unmanned missions. For parts shielded with less than ~40 mils Al, doses exceeding 25 krads (Si) are possible. Hence, it is clear that significant shielding may be required to shield both

Table 4
Doses in silicon for hypothetical worst case solar energetic particle events based on the Carrington event of 1859 (Townsend et al., 2003)

Al shield thickness (g cm^{-2})	Carrington event	
	September 1989 spectrum dose (krad (Si))	March 1991 spectrum dose (krad (Si))
0.1	25.9	53.9
0.3	14.6	25.8
0.5	10.2	16.1
1	5.7	7.3
5	0.98	0.6

components and human crews in deep space, and in near polar orbits since these events will have access into lower altitude polar regions.

4. Revised estimates of possible Carrington event doses

Prior analyses of possible doses from a Carrington-type event, reviewed in the previous two sections, assumed a wide range of possible spectral shapes, ranging from soft to hard. For an assumed hard spectrum, the doses in human organs and in electronics were found to be very large and problematic. In other recently reported work, however, it is thought that the Carrington event must have had a soft spectrum because of the lack of ^{10}Be production during the event, as recorded in the ice core data (Beer et al., 1990; Smart et al., 2005). In the latter work, it is suggested that the Carrington event may have had a spectrum very similar to that of the August 1972 event. Hence, in an effort to provide more plausible estimates of crew organ doses and electronic doses from a Carrington-type event, we have carried out calculations using the BRYNTRN code for such an event composed of an August 1972 spectrum normalized to the >30 MeV proton fluence from the ice core data (McCracken et al., 2001). The event spectral parameters are listed in Table 1. Organ doses for crews in deep space, as a function of spacecraft aluminum shield thickness (up to 50 g cm^{-2}) are displayed in Fig. 1. For aluminum thicknesses $\leqslant$10 g cm^{-2} these results are identical to the earlier results presented in Table 3. The results for aluminum thicknesses >10 g cm^{-2} represent an extension of the previously reported results in Stephens et al. (2005).

Behind 1 g cm^{-2} aluminum shielding (slightly thicker than a space suit) this event yielded a dose of 1.4 Gy (2.1 Gy-Eq), which is severe and could result in nausea, emesis, malaise, hematologic damage, and a slight possibility of death. At typical spacecraft shielding thicknesses (5–10 g cm^{-2} aluminum) a BFO dose in the range of 0.21–0.70 Gy-Eq was calculated. Acute radiation syndrome response symptoms in this range are unlikely and of little or no concern (NCRP, 2000). Note that 10 g cm^{-2} aluminum is sufficient to reduce the BFO dose lower than the 0.25 Gy-Eq level (current 30d limit for missions in low-Earth orbit). Skin doses for space suit shielding (1 g cm^{-2}) for an event of this type could be as large as 34 Gy (51 Gy-Eq). For the eye doses could be as large as 24 Gy (36 Gy-Eq). Possible symptoms include lens cataracts, keratitis, erythema, epilation and moist desquamation (NCRP, 2000). For typical space craft shielding thicknesses (~10 g cm^{-2}) the calculated doses are 1.2 Gy (1.8 Gy-Eq) for the skin and 1.1 Gy (1.6 Gy-Eq) for the eye. Comparing these doses to those described in Section 2.2 for a spectral shape similar to the September 1989 event, we note that the softer spectrum used here results in severe biological damage to crews only if they are in a relatively unprotected area (such as outside the spacecraft in a spacesuit). For any reasonable spacecraft shielding thickness the organ doses do not present a significant risk to crew members.

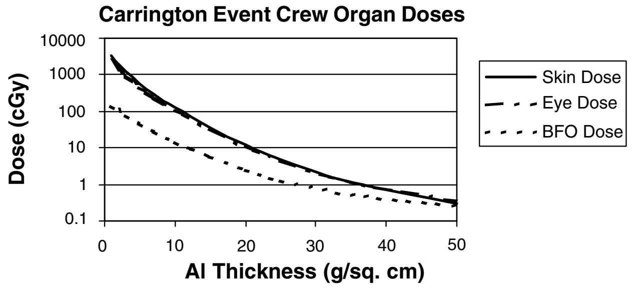

Fig. 1. Organ doses versus aluminum shield thickness for crews in deep space for a Carrington-type event based upon the August 1972 solar energetic particle event spectrum.

Table 5
Doses in silicon for the hypothetical Carrington event using the August 1972 spectrum shape

Al shield thickness (g cm^{-2})	Carrington event August 1972 spectrum dose (rads (Si))
0.1	13,611
0.3	10,414
0.5	8495
1	5341
2	3020
3	1904
5	881
7	456
10	191
15	54.3
20	18
25	6.7
35	1.3
50	0.27

Table 5 presents total ionizing dose (TID) in silicon for electronics shielded by aluminum thicknesses ranging from ~15 mils (0.1 g cm^{-2}) up to 50 g cm^{-2}. Comparing these predictions with those presented in Table 4, we notes that the doses obtained with the August 1972 spectral shape are much lower for very thin shields ($\leqslant$1 g cm^{-2}), but comparable at 5 g cm^{-2} aluminum shield thickness. The newer calculations extend the data out to 50 g cm^{-2}. These TID values are not a problem for nominal spacecraft shielding (thicknesses $\geqslant$5 g cm^{-2}).

5. Concluding remarks

Recent measurements of nitrates in ice core samples make available a history of integral fluences of large SPEs over a period covering the last ~500 years. This information can be used to estimate a plausible, hypothetical worst case SPE for use in interplanetary mission planning. Given the lack of spectral shape information in the ice core methods, spectral shapes from large space era SPEs can be used in combination with the 30 MeV fluence measurement for the Carrington Flare of 1859 to estimate critical organ doses from such an event. Reviews of earlier works (Townsend et al., 2003; Townsend et al., 2004; Stephens et al., 2005) estimating organ and electronics doses were presented. The largest doses were typically received for the September 1989 spectral form. However, consideration of the ^{10}Be concentration in the ice core samples suggests that this spectrum is unreasonably hard. Hence, a reanalysis is carried out using the August 1972 spectral shape, which appears to be a more reasonable assumption (Smart et al., 2005). Except for very thin shields, crews and electronics should be protected from significant risk from a Carrington-type event by spacecraft shielding thicknesses that are $\geqslant 5$ g cm^{-2}. However, the results obtained in earlier work (Stephens et al., 2005; Townsend et al., 2003) suggest that the estimated doses are fairly sensitive to the spectral hardness.

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