Carrington Flare of 1859 as a Prototypical Worst-Case Solar Energetic Particle Event

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***Abstract*—Recent analyses of ice core samples indicate that the Carrington flare of 1859 was the largest event observed in the past 500 years. These ice core data yield estimates of the proton fluence for energies greater than 30 MeV, but provide no other spectrum information. Assuming that the proton energy distribution for such an event is similar to that measured for other recent, large events, total ionizing doses in deep space are estimated for these hypothetical worst-case spectra. These estimated doses, as large as 50 krad (Si), could be catastrophic for sensitive electronic devices unless substantial shielding is provided.**

***Index Terms*—Cosmic rays, environmental radiation effects, extraterrestrial exploration, radiation monitoring, solar radiation.**

I. INTRODUCTION

SOLAR particle events (SPE) have historically been of concern for space missions due to the possibility of exposing onboard equipment and crews to large radiation doses that may be mission or life threatening. Most SPEs have too few energetic protons to be a concern to missions in deep space. Very large events that pose significant risks to spacecraft components and/or crews typically occur once or twice during an 11-year solar cycle. As the duration of a mission increases, the possibility that a significant dose from an SPE will be delivered also increases. Therefore, for mission planning purposes a realistic, hypothetical worst-case solar particle event spectrum can provide a reasonable upper bound on radiation doses for these events.

In this work, estimates of electronic component doses for several plausible worst-case solar particle events are made. Previous analyzes of some hypothetical worst-case events for protection of spacecraft crews are summarized elsewhere [1] and typically involve spectra obtained by combining various events or arbitrarily scaling measurements of large events that previously occurred during the past four decades of the space era. For this work, we take a different approach and develop 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 [2]. These nitrate measurements provide estimates of the integral fluence of protons above 30 MeV for such events. For this 500 year period the "Carrington" solar flare of 1859 had the largest estimated omnidirectional fluence of protons >30 MeV with a value of 18.8×10^9 cm^{-2}. This fluence level is the value at the top of the polar atmosphere (in space at the Earth orbit). Hence, it is an excellent candidate for a plausible worst-case solar particle event.

TABLE I
SPECTRAL PARAMETERS USED IN THIS WORK FOR THE WEIBULL PARAMETERIZATIONS OF THE CARRINGTON FLARE EVENT

Spectrum Shape Used	Φ_0 (protons cm^{-2})	k	α
Sep-89	4.79E+11	0.877	0.3841
Mar-91	1.47E+12	0.972	0.441

Since one fluence datum at a single energy does not constitute a spectrum, a spectral shape must be assumed. Therefore, to generate plausible spectra, the Carrington flare fluence for >30 MeV protons, as reported by McCracken *et al.* [2], is used as an overall normalization point in combination with the measured spectral shapes of two large solar particle events from the space era, September 1989 and March 1991, to create hypothetical worst-case solar particle event spectra. Motivation for this investigation came from a recent analysis of the Carrington Flare as a hypothetical worst-case event for human exposures in deep space [3]. That work indicated that critical organ doses would be substantial enough to be life threatening for crews and indicated that estimating doses for electronics was warranted as well. For example, skin doses as large as 56 Gy [5600 rad (water)] were calculated behind 1 g/cm^2 Al shielding for the Carrington Flare with a March 1991 spectral shape. In addition, reducing the bone marrow dose below the currently recommended 30d crew limits for low-Earth orbiting missions [4] of 0.25 Gy (25 rad) required nearly 50 g/cm^2 Al shielding (about 18 cm) for the Carrington Flare with a September 1989 spectral shape. Since many electronic components are less shielded than the crew quarters shielding considered in that study, total ionizing doses received in deep space by electronic components from a Carrington-type event could be substantially larger, and may result in component failure, especially for many COTS parts.

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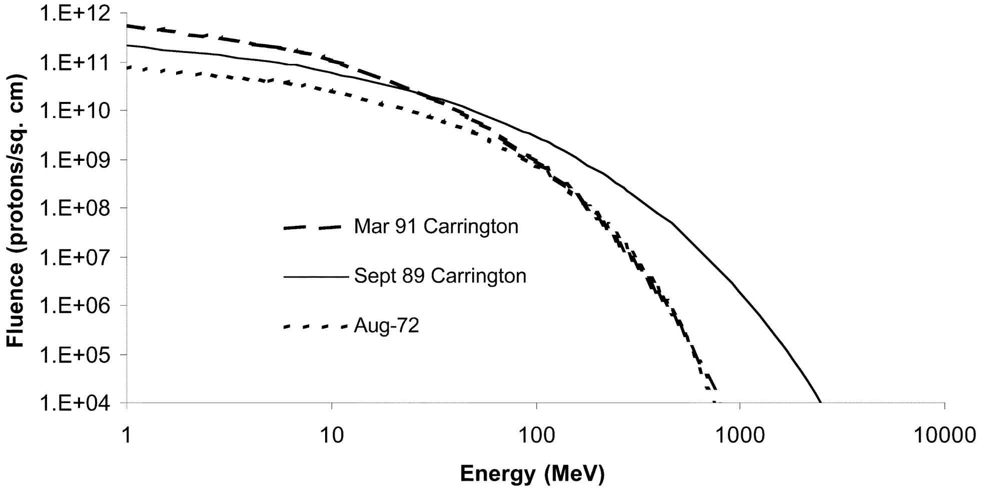

Fig. 1. Carrington flare proton fluence spectra with the September 1989 (solid line) and March 1991 (long dashed line) Weibull spectral shapes compared with the August 1972 event (short dashed line).

II. METHODOLOGY

A. Solar Energetic Particle Event Spectra

Worst-case SPE proton spectra, based on the spectral shapes of large space era events with their total fluence above 30 MeV datum normalized to the Carrington flare fluence value of 18.8×10^9 cm^{-2}, are assumed. Specifically the spectral shapes of the 29 September 1989 and 23 March 1991 events are used. Energy (Weibull) parameterizations of the input spectra of these events obtained from the work of Xapsos are used [5]. These two events were selected since they yielded the largest doses for thin and thick shields in the analyses reported in [3]. Recent studies indicate that the exponential in energy form more accurately represents the measured proton spectra for these events [5]. The exponential in energy form is

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

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 spectrum. They are listed in Table I.

Note that the magnitude of the September 1989 Carrington flare spectra is $\sim 13\times$ larger than the actual September 89 spectrum and the magnitude of the Mar-91 Carrington flare spectrum is $\sim 9\times$ larger than the actual March 1991 spectrum.

Fig. 1 displays the fluence spectra for the Carrington Flare with the September 1989 and March 1991 Weibull spectrum shapes, from (1), compared to the spectrum for the August 1972 event. The August 1972 spectrum is presented only for purposes of comparing spectra. No doses for this event are presented. Note that the March 1991 spectrum is softer than both the other spectra, but has larger numbers of protons at lower energies. Hence, it may yield the highest doses for very thin shields but is likely to be surpassed by the doses obtained from the September 1989 spectrum behind even moderate shielding. Note also that the September 1989 Carrington flare spectrum is significantly higher at all energies than the August 1972 spectrum.

B. Dose Calculations

Doses in silicon are calculated for these assumed worst-case events using the BRYNTRN space radiation transport code [6] for five thicknesses of aluminum shielding in free space. These areal densities are 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. The BRYNTRN space radiation transport code transports incident SPE protons (and their secondary protons, neutrons, deuterons, tritons, ^{3}He and alpha particles generated by nuclear interactions in the shield) through the aluminum shielding. Hence, the doses reflect contributions from all of these particles. Incident SPE alpha and heavy ion fluxes are not included in these analyses 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 are probably underestimates of the actual doses to be expected from such an event, especially for the very thin shields, where the ranges of the heavy ions are substantially larger than the shield thickness.

III. RESULTS

Doses in Si for the two Carrington flare spectra are displayed in Table II for each assumed shield thickness. 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 in Xapsos [5, Fig. 5]. For 0.5 g/cm^2 ($\sim$73 mils), the March 1991 predicted dose value presented herein exceeds the 100% confidence level worst-case value presented in Xapsos [5] by nearly a factor of 2 (16 versus 9). The predicted dose value of 10.2 krad for the Carrington September 1989 soft spectrum behind 0.5 g/cm^2 ($\sim$73 mils) Al, however, is very close to the Xapsos value of 9 krad (Si). These differences, however, may not be significant given that the spectra used herein are composed of an assumed spectral shape with a fluence magnitude obtained from ice core data.

TABLE II
DOSES IN SILICON FOR HYPOTHETICAL WORST CASE SOLAR ENERGETIC PARTICLE EVENTS BASED ON THE CARRINGTON FLARE OF 1859

Al Shield Thickness (g/cm^2)	Carrington September 1989 Spectrum Dose (krad (Si))	Carrington 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

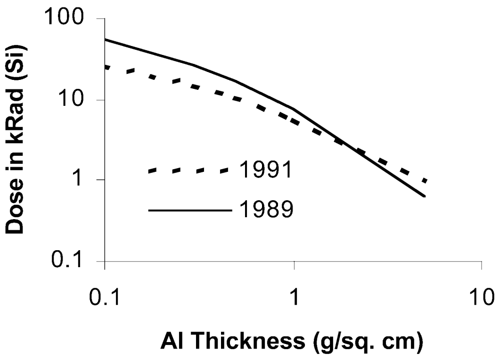

Fig. 2. Dose in krad (Si) as a function of Al shield areal density. Results are displayed for the March 1991 (solid) and September 1989 (dash) Carrington flare spectra.

Note also that 15 mils is probably much less shielding than any component would have on a modern spacecraft.

Fig. 2 displays the doses given in Table II. Note that the curves are nearly straight lines from 0.1 to 1 g cm^{-2} Al areal densities, which is similar to the trend displayed in Xapsos [5, Fig. 5], indicating that a simple parameterization of dose as a power function of shield thickness is proper. However, the downward bending of the curves for shield thicknesses greater than 1 g cm^{-2} suggests that a simple parameterization may not be valid for thicker shields.

Total ionizing doses ~ 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 likely. Hence, it is clear that significant shielding may be required to shield both components and human crews in deep space, and in near polar orbits since these events will have access into lower altitude polar regions.

IV. CONCLUSION

In this work, we have used recently reported data from ice core samples of the proton fluence for the Carrington flare of 1859 as a hypothetical upper bound on dose estimates for electronic components in deep space. Assumed spectral shapes based on the March 1991 and September 1989 events were normalized to the reported ice core data fluence value of 18.8×10^9 cm^{-2} for protons with energies ≥ 30 MeV were used as input into transport calculations. Doses in silicon shielded by Aluminum shield thicknesses comparable to those found in manned and unmanned spacecraft were calculated and found to be as large as 54 krad (Si). The values obtained are not only life-threatening for crews of manned missions, but present a significant hazard to onboard electronics.

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