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Interplanetary crew dose estimates for worst case solar particle events based on historical data for the Carrington flare of 1859

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Abstract

Over the past two decades, hypothetical models of "worst-case" solar particle event (SPE) spectra have been proposed in order to place an upper bound on radiation doses to critical body organs of interplanetary crews on deep space missions. These event spectra are usually formulated using hypothetical extrapolations of space measurements for previous large events. Here we take a different approach. Recently reported analyses of ice core samples indicate that the Carrington flare of 1859 is 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, interplanetary crew doses are estimated for these hypothetical worst case SPE spectra. These estimated doses are life threatening unless substantial shielding is provided.

1. Introduction

Solar particle events (SPE) have historically been of concern for crewed space missions due to the potential for exposing crews to large radiation doses that may be mission—or life threatening. During the space era many SPEs have been observed. Most have too few energetic protons to be a concern to interplanetary crews. Very large events that pose significant health risks to crews typically occur once or twice during an 11-year solar cycle. 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 interplanetary crew organ doses for several plausible worst-case solar particle events are made. Previous analyses of hypothetical worst-case events are summarized elsewhere [1] and 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. 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 nitrates are produced in

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the upper atmosphere by several different physical and chemical mechanisms. A particularly important mechanism is ionization resulting from the impacts of energetic protons with the atmospheric constituents. The nitrates are quickly deposited in the snow pack in the polar regions by water droplets and ice crystals falling as precipitation. Over time the snow consolidates to high-density firn. The thin nitrate layer concentration from each large event can be extracted from ice core samples taken from the firn in the polar regions (Greenland and the Ross Ice Shelf). Annual variations can be deduced along with impulsive increases that are correlated, with a high degree of reliability, with major solar particle events that have occurred over time. A conversion factor to relate solar proton fluences above 30 MeV to the measured nitrate concentration in the ice core has been extracted and gives predictions that compare favorably with measurements of solar proton fluences from satellites during the space era. These nitrate measurements can then be used to provide estimates of the integral fluence of protons above 30 MeV for such events. Details of the methodology are available in McCracken et al. [2] and references therein. For this 500 year period the "Carrington" solar flare of 1859 had 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 is an excellent candidate for a plausible worst-case event. Unfortunately, one fluence datum at a single energy does not constitute a spectrum. Therefore, to generate plausible spectra, the Carrington flare fluence for >30 MeV protons, reported by McCracken et al. [2] is used as an overall normalization or scaling point in combination with the measured spectral shapes of several large solar particle events from the space era to create hypothetical worst-case solar particle event spectra.

2. Methodology

Five worst-case SPE proton spectra, based on the spectral shapes of large space era events with the 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 4 August 1972, 12 August 1989, 29 September 1989, 19 October 1989 and 23 March 1991 events are used. Both exponential in rigidity (momentum per unit charge) [3] and energy (Weibull) [4] parameterizations of the input spectra of these events are used, yielding 10 input proton spectra for analysis. The exponential in rigidity form is

$$J = J_0 \exp(-R/R_0), \tag{1}$$

where J is the integral fluence (protons/cm^2) exceeding some energy E and R is the proton rigidity in MV (momentum per unit charge). The J_0 and R_0 parameters are determined from the proton spectral data using a least squares analysis. Values are listed in Table 1. This parameterization is the one most commonly used for previous analyses [1].

Recent studies indicate that the exponential in energy form more accurately represents the measured proton spectra for these events [4]. The exponential in energy form is

$$J = J_0 \exp(-kE^{\alpha}), \tag{2}$$

where J is as before, E is the proton energy in MeV, and k and α are parameters used to fit the spectrum. They are listed in Table 2.

Table 1
Spectral parameters for Carrington flare event in the rigidity parameterization form

Spectra shape used	J_0 (protons cm^{-2})	R_0 (MV)
Aug-72	2.87E+11	87.78
Aug-89	1.13E+12	58.42
Sep-89	1.91E+11	103.05
Oct-89	2.45E+11	93.15
Mar-91	4.29E+12	44.03

Table 2
Spectral parameters for Carrington flare event in power law parameterization form

Spectrum shape used	J_0 (protons cm^{-2})	k	α
Aug-72	5.23E+10	0.0236	1.108
Aug-89	1.81E+12	1.166	0.4015
Sep-89	4.79E+11	0.877	0.3841
Oct-89	4.64E+12	2.115	0.2815
Mar-91	1.47E+12	0.972	0.441