SEP Event Distribution Function as Inferred from Spaceborne Measurements and Lunar Rock Isotopic Data

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Abstract

The differential and integral distributions of the satellite-measured cycle 20-22 SEP events are analyzed as relevant to the last million of years-long impact of the mean solar proton fluxes on lunar rocks.(Reedy, 1966). The two sets of data indicate that the SEP event distribution function gets steeper as the SEP fluence size increases. The distribution can be described by a power-law function with exponential steepening for large fluences. The parameters have been found for the distribution that covers the $\geq$30 MeV solar proton fluence range from 10^6 to 10^{11} cm^{-2}.

1   Introduction

Whereas the distributions of most of the solar radiation species have been found to be power-law functions, the SEP events, inferred from the direct particle observations, are assumed to be distributed either by a power law (van Hollebeke et al., 1975, Goswami et al., 1988, Gabriel and Feynman, 1996) or log-normally (Goswami et al., 1981, Feynman et al.,1993) .

The uncertainty in the distribution functions is due essentially to the following two circumstances. First, a set of experimental low-fluence event data are used, for which the threshold effects of detection and separation are significant. In the case of SEP event $\geq$30 MeV protons, the fluence detection and separation threshold is about $2 \cdot 10^7$ proton/cm^2 (Kurt and Nymmik, 1997). Second, most of the researchers (Lingenfelter and Hudson, 1980; Gabriel and Feynman, 1996) note that the distributions steepen considerably in the range of $\geq$30 MeV proton fluences above 10^9-10^{10} cm^{-2}. The same effect follows from the SEP event proton-produced radionuclides activity in lunar rock samples (Reedy, 1996). The steepening effect in the distribution seems to be natural because of the natural restrictions on the SEP number and total particle energy in each of the SEP events.

This paper is aimed at joint statistical and functional analysis of the SEP event proton data obtained from the spacecraft and lunar radionuclide measurements with a view to finding the distribution function form for extremely large fluences.

2 Analysis of Spacecraft Measured SEP Fluence Data

It is of importance that such an analysis must only be made using a homogeneous set of spacecraft measurement data. So, we disregarded the indirect SEP event proton fluence data of cycle 19, which were used in some of the earlier works (Goswami, 1980; Gabriel and Feynman, 1996; Kurt and Nymmik, 1997), and used only the IMP-7 and 8 proton fluence data of cycles 20-22. Moreover, both differential and integral distributions are used in our analysis.

We analyzed four versions of power-law functions (Eq.1) for $\geq$30 MeV proton fluences

$$\frac{dN}{d\Phi} = C \cdot \left(\frac{\Phi}{\Phi_c} \right)^{-\gamma} \tag{1}$$

differing in the character of their power-law indices (except for version IV below) The spectral indices for these versions are

(I) the same for all fluences, $\gamma \equiv \gamma_o$;

(II) different for low (γ_0) and large (γ_1) fluences, with the transient point at fluence size Φ_c;

(III) constant, γ_o, below fluence size Φ_c and steadily rising, γ_2, above Φ_c, with $\gamma_2 = \gamma_o \cdot (\Phi/\Phi_c)^{\alpha}$;

(IV) the same as version (I), but divided by the fluence size exponent, $\exp(\Phi/\Phi_c)$:

$$\frac{dN}{d\Phi} = C_1 \cdot \frac{\Phi^{-g}}{\exp\left(\dfrac{\Phi}{\Phi_c}\right)} \tag{2}$$

The above functions were used earlier to describe the various distributions of solar radiation events in different papers, but function (III) in the large-fluence range is identical to the log-normal function.

All four functions were compared with experimental data represented by differential and integral distributions simultaneously. In each of the cases, we obtained the standard deviation S of the calculated function Φ_{cal} from the differential and integral distributions Φ_{exp} of experimental data for the set of the function parameters (C, γ_o, γ_1, γ_2, Φ_c, and α), for which the S value was minimum. In the test calculations, we used the experimental data for fluences $\Phi \geq 10^7$ proton/cm^2 and take into account the statistical deviation of the experimental data.

The calculated standard deviations for the best parameters of above-mentioned versions are $S_1 = 3.7 \cdot 10^{-2}$, $S_2 = 1.46 \cdot 10^{-2}$ ($\gamma_1 = 3.0$, $\Phi_c = 1.1 \cdot 10^9$), $S_3 = 1.34 \cdot 10^{-2}$ ($\alpha = 0.075$, $\Phi_c = 1.3 \cdot 10^8$) and $S_4 = 1.35 \cdot 10^{-2}$ ($\Phi_c = 6 \cdot 10^9$). It should be noted that these parameters are not the best ones of either differential or integral distribution taken separately. Except for version (I), the deviations of all functions are close to each other. This means that the present-day experimental spacecraft-measured SEP distribution data are insufficient for the advantages of different mathematical models to be tested. Some results of the above test are presented in the Fig. 1, which shows the experimental data on the differential and integral distributions and the calculation results for versions (I), (II), and (IV). The difference between the model representation and the experimental data at $\Phi_{30} < 10^7$ proton/cm^2 is due to the SEP event detection threshold effect.
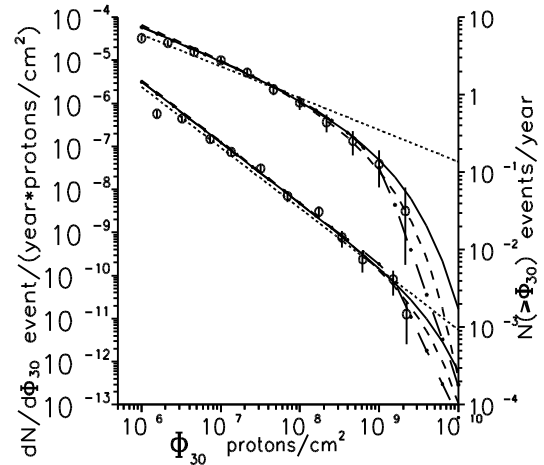

Figure 1: The differential (the left scale, and the lower data) and integral (the right scale and the upper data) distributions. The dots are the experimental data, the long-dashed line is the 1st , the dotted line the 2nd, and the solid line the 3rd, version, and the short-dashed line is the 4th version of the distribution function. .

3 Distribution Function Inferred from Lunar Rock Radionuclides Data

Reedy (1996) reported the data on the omnidirectional ≥ 30 MeV SEP event proton fluxes derived from lunar rock radionuclides generated over periods of a few millions of years. The data

inferred from more precise measurements of three isotopes proved to be 25 (^{26}Al, half-life $7.3 \cdot 10^5$ years), 21 (^{21}Ne, $2.0 \cdot 10^6$), and 25 (^{53}Mn, $3.7 \cdot 10^6$) proton/(cm^2·s). Using the set of measured fluxes, Reedy (1996) found the upper limits of the distribution function for the SEP events with ≥10 MeV proton fluences as $\Phi_{10} > 10^{14}$ proton/cm^2. An extreme assumption was made by Reedy, that all of the above radioactive nuclides were produced by a single huge SEP event as long ago as one half-life of each of the radionuclides (see Fig. 3).

The present paper describes the results of calculating the SEP event proton fluxes for the exposure times ranging from $7 \cdot 10^5$ to $3.7 \cdot 10^6$ years in terms of the distribution function model versions (II)-(IV). The results obtained are compared with experimental data in an attempt to find the SEP event distribution function.

The following assumptions and regularities are used. The mean solar activity level during the last million years is assumed to be the same as during solar cycles 20-22, for which period we have the experimental SEP flux data (Fig. 1). The mean solar activity of the period has been found to be <W>=74.4 (the mean annual sunspot numbers), while the mean annual SEP occurrence frequency (according to Nymmik, 1999) is proposed to be 7.94 SEP events (with ≥30 MeV proton fluences $\Phi_{30} \geq 10^6$ proton/cm^2). The fluence size for each of the SEP events was generated to be a random value (to define the statistical effects) corresponding to each of the distribution function versions. The calculated total proton fluence, which has been accumulated for millions of years was then divided by the exposure time and compared with experimental data. The "best" model parameters can be inferred from the comparison results.

Fig. 2 shows the dependence of the results of calculating the millions-of-years-averaged flux in terms of model (IV) on the parameter Φ_c. It is seen that in this case the value of the exponential cutoff $\Phi_c = 4 \cdot 10^9$ is lower than $\Phi_c = 6 \cdot 10^9$ inferred from spacecraft data.

In the above manner, it proved to be possible to determine the best parameters for all (II)-(IV) models. Also, functions (II)-(IV) with these parameters can well explain the proton flux inferred from the lunar rock radioisotope data. Bearing this fact in mind, we must resort to additional reasoning to select an authentic distribution function out of the three. We use the total SEP event particle number or total particle energy that can be emitted from the Sun as the selection criterion. The relevant analysis has shown that all of the models, except for version (IV), predict the occurrences of the SEP events with fluences $\Phi_{30} > 10^{12}$ proton/cm^2 at E ≥ 30 MeV over a few millions of years. Model (IV) alone predicts a proton fluence of a few units of 10^{10} and a total particle energy of 10^{33} - 10^{34} ergs, which is in agreement with some of the solar physics concepts discussed nowadays.

4 Conclusion

The differential and integral distributions of the satellite-measured cycle 20-22 SEP events analyzed together with the mean solar proton fluxes inferred from the lunar rock radionuclide data (Reedy, 1966) have made it possible to find the distribution function form in the range of large SEP event proton fluences. This distribution establishes a lower occurrence probability for the large-fluence SEP events compared with the log-normal function (Feynman et al., 1993). According to the distribution function, the largest SEP event, which might appear, is determined to be some units of·10^{10} proton/cm^2.
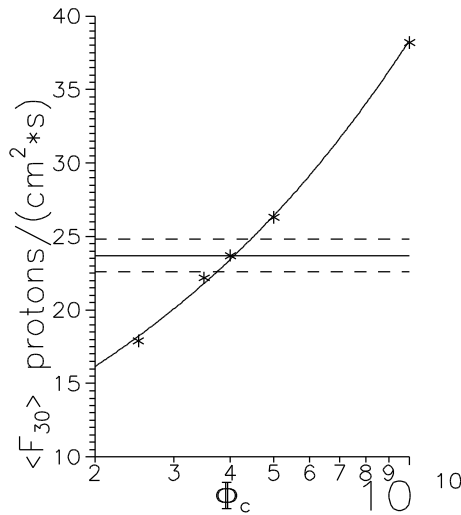
Figure 2: The averaged proton flux data for million of years exposure on the Moon. The horizontal lines are the experimental data with their deviations for 3 radionuclides by Reedy (1996). The circles are the calculation result for some values of parameter Φ_c (model version (IV)).
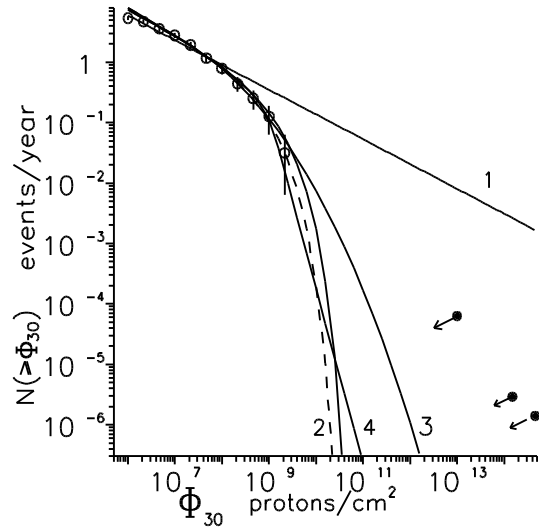
Figure 3: The data on the integral SEP event proton distribution. The circles are the spacecraft measurement data, the dots are the upper limit of the function calculated by the data and method of (Reedy, 1996). Curve: 1 is the version (I) data. Curve 2 is the version (IV) results (the solid line is the best function for the spacecraft measurement data, the solid line is the best function for the radioisotope data). Curve 3 is the version (II) data.

5 References

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