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Extreme fluxes in solar energetic particle events: Methodological and physical limitations☆

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HIGHLIGHTS

- All available data on the largest solar proton events (SPEs) are analyzed.
- Distribution function obtained for 3 last cycles is confirmed for 41 solar cycles.
- Estimates of extremely large fluences in the past are found to be overestimated.
- Extremely large SEP fluxes are shown to obey a probabilistic distribution.
- Limitations are obtained for the extrapolation of the results to the past/future.

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ABSTRACT

In this study, all available data on the largest solar proton events (SPEs), or extreme solar energetic particle (SEP) events, for the period from 1561 up to now are analyzed. Under consideration are the observational, methodological and physical problems of energy-spectrum presentation for SEP fluxes (fluences) near the Earth's orbit. Special attention is paid to the study of the distribution function for extreme fluences of SEPs by their sizes. The authors present advances in at least three aspects: 1) a form of the distribution function that was previously obtained from the data for three cycles of solar activity has been completely confirmed by the data for 41 solar cycles; 2) early estimates of extremely large fluences in the past have been critically revised, and their values were found to be overestimated; and 3) extremely large SEP fluxes are shown to obey a probabilistic distribution, so the concept of an "upper limit flux" does not carry any strict physical sense although it serves as an important empirical restriction. SEP fluxes may only be characterized by the relative probabilities of their appearance, and there is a sharp break in the spectrum in the range of large fluences (or low probabilities). It is emphasized that modern observational data and methods of investigation do not allow, for the present, the precise resolution of the problem of the spectrum break or the estimation of the maximum potentialities of solar accelerator(s). This limitation considerably restricts the extrapolation of the obtained results to the past and future for application to the epochs with different levels of solar activity.

1. Introduction

Long-term observations of solar proton events (SPEs), or solar energetic particle (SEP) events, have given a number of indications that approximately once during a given solar cycle, an event occurs whose fluence above a given energy (usually ≥10, ≥30, ≥60 and ≥100 MeV for protons) dominates the fluence of the entire cycle (e.g., Shea and Smart, 1990). It may overlap the fluences from the other events and even determine, in fact, a total fluence for the cycle. Such rare phenomena are sometimes called "rogue events" (Kallenrode and Cliver, 2001) in analogy to rogue ocean waves that have unusually large amplitudes. Well-known examples of rogue

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SEP events at the Earth occurred on 14 July 1959, 4 August 1972, 19 October 1989 and 14 July 2000. Rogue events have also been observed in the inner heliosphere – with *Helios* 1 on 4 November 1980 at 0.5 AU and with *Ulysses* in March 1991 at 2.5 AU. The origin of these rogue events is thought to be related to multiple coronal mass ejections (CMEs) and converging interplanetary shocks. If observed at the Earth's orbit, these rare extreme events become important geophysically and practically (e.g., radiation hazard for spacecraft).

In some cases, extreme SEP events in the non-relativistic energy range are accompanied by large fluxes of relativistic protons ($E_p \geq 500$ MeV), or solar cosmic rays (SCRs). They are usually registered by neutron monitors (NMs) at the Earth's surface (GLE phenomena, or Ground Level Enhancement of SCRs). Recently it was suggested (Crosby, 2009) that rare Solar Extreme Events (SEEs) be defined as those events in which the characteristics (field strength, speed, intensity of radiation, energies, etc.) of the associated phenomena (solar flares, CMEs, SEP events) are some orders of magnitude larger than those in most other events (e.g., the event of 20 January 2005).

At present, the so-called "Carrington event" of 1–2 September 1859 (Townsend et al., 2003, 2006) seems to be one of these "rare SEEs". As follows from Smart et al. (2006, 2007), the Carrington event (CE) had the largest integral fluence Φ of protons with energies of $E \geq 30$ MeV (i.e., the energy-integrated fluence above a certain energy value) in the approximately 450-year period starting in 1561. There is no doubt that the study of such rare events is of paramount importance. In particular, Townsend et al. (2003, 2006) have suggested that, henceforth, the CE, which had an integral fluence of $\Phi(\geq 30\ \text{MeV}) = 1.88 \times 10^{10}\ \text{cm}^{-2}$, should be considered to be the best reference "worst case" for estimates of radiation hazard in space.

Indeed, the two nearest candidates for the role of the "worst case" – the events of 15 November 1960 and 4 August 1972 – were characterized by far lesser values of $\Phi(\geq 30$ MeV), approximately $9 \times 10^9\ \text{cm}^{-2}$ and $5 \times 10^9\ \text{cm}^{-2}$, respectively (Smart et al., 2006). Note, however, that those fluence values were calculated from data that were obtained in the epoch of historically fragmentary and indirect measurements of SEP fluxes. At the present time it has become clear that such early energy spectra have the analytical forms that are quite different from the spectral form that has recently been established (Nymmik, 2011c). For this reason, the fluence values for the events of 1960 and 1972 should be critically discussed in light of the new summary distribution function (see Section 2). Also of great interest are the estimation of the occurrence probabilities of such rare events at the present level of solar activity and the possible extrapolation of the obtained results to the remote past of the Earth (e.g., Wdowczyk and Wolfendale, 1977; Kiraly and Wolfendale, 1999).

As we know from our own long-term experience of studying solar cosmic rays, rare large solar events do not form some specific "class" of solar phenomena. They seem to constitute part of the common ensemble of SEP events because there is no sharp boundary between this "class" and the rest of the events. SEP events are described by a single distribution function, and SEEs naturally form its "tail" in the low probability range. This point of view has been confirmed, in particular, by the recent results of Crosby's (2009) analysis: SEEs are part of the global distribution of all events rather than "outliers" with their own special characteristics.

Our present study was greatly inspired by the publication of new data on proton fluences for a number of large events from 1561 to 1994 identified by the so-called nitrate method (McCracken et al., 2001) and by the results of the analysis and interpretation of those events (e.g., Townsend et al., 2003, 2006; Smart et al., 2006, 2007). At the same time, we relied upon our own experience of research in this field (e.g., Miroshnichenko, 1994, 1996, 2001; Nymmik, 1999a,b,c; 2007a,b,c). After providing a general Introduction to this paper (Section 1), we study the distribution function of proton fluxes with energies of ≥30 MeV (Section 2) and consider the possibility of its extrapolation to the range of flux magnitudes that are presently inaccessible to measurements with the level of solar activity taken into account. Furthermore (Section 3), we analyze the general features of the energy-spectrum shape for protons, methods for describing them and the relations between the spectral form and the event size.

Fluence energy spectra for a number of large SEP events are considered in Section 4 by drawing on the data from the Carrington event. Section 5 is devoted to the analysis of peak proton fluxes for extreme events that are comparable to the CE flux. Based on the above consistent approach to the presentation of the distribution function of SEP fluxes and the analysis of the peculiarities of their spectra, we also discuss here the maximum capabilities of solar accelerator(s), namely, we estimate the probabilities of generation (appearance) of extremely large fluxes of SCRs. In Section 6, we summarize our results and give a number of concluding remarks.

2. Distribution function of proton fluences

Distribution functions of SCR events with proton fluences of energy ≥30 MeV, or $\Phi(\geq 30$ MeV), have been widely investigated (see, e.g., Nymmik, 2011c, and references therein). These functions are constructed, as a rule, based on the data from SEP events whose sizes are determined by measurements onboard the satellites of the *IMP* and *GOES* series. At present, the available data sets cover, depending on the selection criteria, approximately 200 events with $\Phi(\geq 30\ \text{MeV}) \geq 10^6\ \text{cm}^{-2}$ (Nymmik, 2011c). To describe the distributions, power-law functions are usually applied, sometimes with a break. This approach, however, allows us to calculate the occurrence probabilities of events with certain fluences only down to a probability of ~0.5% (~1/200), which is clearly insufficient for extreme estimates.

Lately, it has become obvious that the accumulation of new satellite data does not enable us to advance considerably in the determination of the form of the distribution function for SEP events as a function of their fluences in the range of low probabilities. An attempt to involve the data concerning cosmogenic isotopes in the lunar soil (Reedy, 1996), unfortunately, has not added any certainty in the resolution of this problem because the isotope data are related to the total (summary) flux of SCR protons with $E \geq 10$ MeV over the past ~10 My but not to individual SEP events.

Some progress on this problem was achieved when the data on the fluences of large SEP events for the period of 1561–1950 were obtained from Greenland ice cores (McCracken et al., 2001). These authors have succeeded, in particular, in estimating the proton fluence for the largest event of that period, namely, the Carrington event, which occurred on 1–2 September 1859; its value was $\Phi(\geq 30\ \text{MeV}) = 1.88 \times 10^{10}\ \text{cm}^{-2}$. Nevertheless, even those data proved insufficient to determine the form of the distribution function in the total diapason of changes of the fluence $\Phi(\geq 30$ MeV). In fact, from those data it was impossible to determine the number of small events that constitute the initial part of the distribution function in the range of fluences $\Phi(\geq 30\ \text{MeV}) = 10^6 \div 3 \times 10^9\ \text{cm}^{-2}$.

Therefore, to calculate the probabilities of extra-large SEP events (and the distribution function) from polar-ice data, it is necessary to know how many single events of fluence $\Phi(\geq 30\ \text{MeV}) \geq 10^6\ \text{cm}^{-2}$ have occurred from 1561 up to the present. In our opinion, the solution to this problem seems to be available.