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Occurrence Probability of Large Solar Energetic Particle Events: Assessment from Data on Cosmogenic Radionuclides in Lunar Rocks

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Abstract We revisited assessments of the occurrence probability distribution of large events in solar energetic particles (SEP), based on measurements of cosmogenic radionuclides in lunar rocks. We present a combined cumulative occurrence probability distribution of SEP events based on three timescales: directly measured SEP fluences for the past 60 years; estimates based on the terrestrial cosmogenic radionuclides ^{10}Be and ^{14}C for the multi-millennial (Holocene) timescale; and cosmogenic radionuclides measured in lunar rocks on a timescale of up to 1 Myr. These three timescales yield a consistent distribution. The data suggest a strong roll-over of the occurrence probability, so that SEP events with a proton fluence with energy > 30 MeV greater than 10^{11} (protons cm^{-2} yr^{-1}) are not expected on a Myr timescale.

Keywords Cosmic rays, solar · Flares, energetic particles

1. Introduction

Advanced knowledge of the occurrence probability of extreme events related to solar energetic particles (SEPs) is very important and acute (Hudson, 2010). This is important from different aspects: from purely astrophysical questions of the highest possible energy released in solar flares (Schrijver *et al.*, 2012) to the geo-environment (Thomas *et al.*, 2013), and even to the technological risk assessments (Shea and Smart, 2012). Direct observations of SEPs cover the past six decades with ground-based and space-borne instruments.

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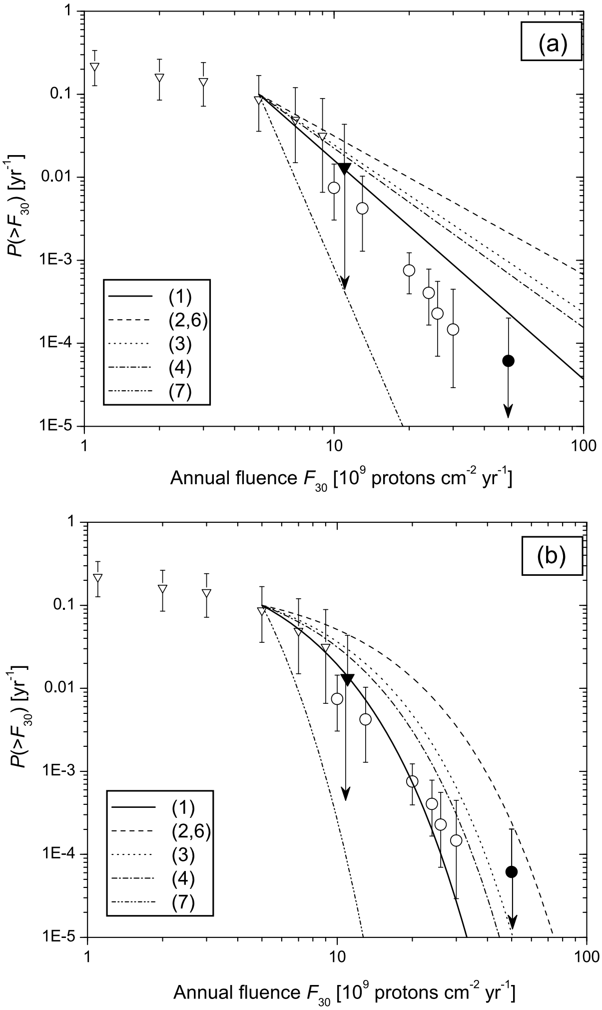


Figure 1 The cumulative OPDF of SEP events (the occurrence probability of events with > 30 MeV fluence greater than the given F_{30}). Points with error bars (90 % confidence interval) correspond to the data for the space era since 1955 (triangles) and cosmogenic radionuclides in terrestrial archives for the Holocene (circles). Open/filled symbols correspond to the measured data and upper estimates, respectively (modified after Usoskin and Kovaltsov, 2012). Curves depict best fits of the high-fluence event tail, obtained in this work from lunar data, for two models—power law [panel (a)] and exponential [panel (b)]. The curves are numbered in the legend, and the numbers correspond to the lines in Table 1. All curves converge at the point corresponding to $P_0 = 0.1$ and $F_0 = 5 \times 10^9$ protons cm^{-2} yr^{-1}.

The cumulative occurrence probability distribution function (OPDF) for the measured proton (> 30 MeV) annual fluences (Shea and Smart, 1990; M. Shea, 2012 private communication) is shown in Figure 1 as triangles with error bars. The average annual SEP fluence (> 30 MeV) obtained from this dataset for the period 1955 – 2007 is $F_{30} = 1.1 \times 10^9$ protons cm^{-2} yr^{-1}. During that period there were four years with F_{30} exceeding 5×10^9 protons cm^{-2} yr^{-1} and no events exceeding 10^{10} protons cm^{-2} yr^{-1}. The latter makes it possible to obtain an upper limit, shown as the filled triangle in Figure 1. Most of these strong-fluence years were dominated by a single SEP event or a series of consecutive events (Smart *et al.*, 2006). One can see a steepening of the OPDF at $F_{30} \approx 5 \times 10^9$ protons cm^{-2} yr^{-1}, which may indicate that stronger events appear more seldom (*e.g.*, Jun *et al.*, 2007). However, the statistics is too low to conclude based on these limited data. Thus, an extension of the SEP data back in time is needed for a better estimate of the OPDF of strong SEP events. Such an extension is possible only on the basis of indirect proxies.

One potential proxy was based on nitrate measured in polar ice (*e.g.*, McCracken *et al.*, 2001; Shea *et al.*, 2006), but it has been shown by Wolff *et al.* (2012) that unfortunately, nitrate from Greenland cannot be used as a quantitative proxy for SEP events. Another potential proxy is related to cosmogenic radionuclides ^{14}C and ^{10}Be in terrestrial independently dated archives, where peaks can be associated with strong SEP events (Usoskin *et al.*, 2006; Usoskin and Kovaltsov, 2012). This method covers the past ten millennia (the Holocene period) and the corresponding cumulative OPDF is shown in Figure 1 as open circles with error bars. This plot has been updated according to Figure 5 of Usoskin and Kovaltsov (2012) by means of combining high- and low-time resolution cosmogenic isotope data and updating the results for the event of 775 AD (Usoskin *et al.*, 2013). No events with an annual fluence greater than 5×10^{10} protons cm^{-2} yr^{-1} have been found, which sets an upper limit, shown as the filled circle in Figure 1. However, this method cannot be applied to longer timescales.

An alternative method for evaluating the average fluence of SEP on very long timescales is based on cosmogenic radionuclides measured in lunar rocks (*e.g.*, Vogt, Herzog, and Reedy, 1990). The method is based on measurements of the depth profile of the nuclide activity in lunar rock samples brought to Earth (*e.g.*, Nishiizumi *et al.*, 2009). Standard radionuclides for this method are ^{14}C (half-life 5.73×10^3 yr), ^{41}Ca (1.03×10^5 yr), ^{81}Kr (2.29×10^5 yr), ^{36}Cl (3.01×10^5 yr), ^{26}Al (7.17×10^5 yr), ^{10}Be (1.36×10^6 yr), and ^{53}Mn (3.74×10^6 yr). However, this method has no time resolution, in contrast to the other methods described above, and only yields the mean SEP flux integrated over a few life-times of the nuclide. In particular, it cannot separate SEP events with high fluence from the background of low-fluence events. Therefore, it is not straightforward to estimate the OPDF for the strong SEP events. For example, Reedy (1996) assumed that the entire SEP fluence measured in a lunar rock was caused by a single huge SEP event that occurred a half-life of that radionuclide ago. This is obviously an extreme assumption that leads to a very conservative upper limit (Reedy, 1996). This limit is not reasonable, however, because there is always a probability distribution of the events, and a huge event cannot appear alone, without a greater number of smaller events occurring as well. However, this conservative upper limit has been used quite widely and was considered as a realistic estimate (*e.g.*, Hudson, 2010; Schrijver *et al.*, 2012).

Here we revise the assessment method for the occurrence probability of SEP events, based on cosmogenic radionuclides measured in lunar rocks, and give a more realistic estimate of the OPDF for strong SEP events, assuming a rational model for the distribution of the event strengths.

2. Modeling

We define the occurrence probability of an SEP event with the annual F_{30} fluence exceeding F as $P(F)$. The mean SEP fluence over a long time-period is defined as

$$\langle F \rangle = \int_0^{F_0} F \cdot p(F) \cdot \mathrm{d}F + \int_{F_0}^{\infty} F \cdot p(F) \cdot \mathrm{d}F = \langle F_1 \rangle + \langle F_2 \rangle, \tag{1}$$

where $p(F) \equiv -\mathrm{d}P(F)/\mathrm{d}F$ is the differential frequency function for an SEP event whose fluence is exactly F. Here we split the mean fluence into two parts: $\langle F_1 \rangle$ is the mean fluence defined by low-fluence ($F < F_0$) but more frequent events, while $\langle F_2 \rangle$ is due to strong-fluence ($F \geq F_0$) but rarer events. As a separation we select the annual fluence $F_0 = 5 \times 10^9$ protons cm^{-2} yr^{-1}. From recent instrumental observations that were continuously conducted since the 1950s we estimate that the total > 30 MeV fluence is $\langle F \rangle = 1.1 \times 10^9$ protons

Table 1 Assessments of the OPDF parameters from different cosmogenic radionuclide data in lunar rocks. Columns correspond to the nuclide, reference to the original data, the measured mean annual fluence F^* (10^9 protons cm^{-2} yr^{-1}), and the corresponding best-fit parameters α and β (10^{-9} cm^2 yr) with a 90 % confidence interval (see text).

#	Nuclide	Reference	F^*	α	β
1	^{14}C	Jull *et al.* (1998)	1.33	2.64 ± 0.21	0.328 ± 0.037
2	^{41}Ca	Fink *et al.* (1998)	1.77	1.67 ± 0.03	0.134 ± 0.002
3	^{81}Kr	Reedy (1999)	1.51	2.01 ± 0.02	0.202 ± 0.003
4	^{36}Cl	Nishiizumi *et al.* (2009)	1.45	2.16 ± 0.02	0.232 ± 0.003
5	^{26}Al	Kohl *et al.* (1978)	0.79	N/A	N/A
6	^{26}Al	Grismore *et al.* (2001)	1.74	1.69 ± 0.01	0.137 ± 0.001
7	^{10}Be/^{26}Al	Nishiizumi *et al.* (1988)	1.10	6.93 ± 0.14	1.19 ± 0.03
8	^{10}Be/^{26}Al	Michel, Leya, and Borges (1996)	0.76	N/A	N/A
9	^{10}Be/^{26}Al	Fink *et al.* (1998)	1.01	N/A	N/A
10	^{10}Be/^{26}Al	Nishiizumi *et al.* (2009)	0.76	N/A	N/A
11	^{53}Mn	Kohl *et al.* (1978)	0.79	N/A	N/A

cm^{-2} yr^{-1}, and $\langle F_1\rangle = 5.2 \times 10^8$ protons cm^{-2} yr^{-1}, *viz.* about half of the total fluence. The corresponding occurrence probability is $P(F_0) = P_0 = 0.1$ yr^{-1} (see Figure 1).

The statistics of the high-fluence events is assessed here using the cosmogenic radionuclide data, measured in lunar samples on the very long timescale. From these nuclides with different lifetimes, ranging from millennia to millions of years, the mean annual fluence of SEP, F^*, was determined based on measurements of their activity in the lunar rocks (see Table 1 and references therein). Here we try to estimate the OPDF for rare high-fluence SEP events based on these data. This was done in the following way. First, the shape of the OPDF tail was *a priori* prescribed. We assumed two models: power-law and exponential tails.

We first assumed that the OPDF has a *power-law* shape in the range of high fluences, with the upper end being fixed at P_0 and F_0,

$$P(F) = P_0\left(\frac{F}{F_0}\right)^{-\alpha}. \tag{2}$$

Then $\langle F_2\rangle$ is directly related to the spectral index α by

$$\langle F_2\rangle = \frac{\alpha}{\alpha - 1} P_0 \cdot F_0. \tag{3}$$

Next we assumed an *exponential* OPDF tail for high-fluence events:

$$P(F) = P_0 \cdot \exp\bigl(\beta(F_0 - F)\bigr). \tag{4}$$

Then the $\langle F_2\rangle$ is directly related to the exponent β by

$$\langle F_2\rangle = P_0 \cdot \left(F_0 + \frac{1}{\beta}\right). \tag{5}$$

For a given value of $\langle F_2\rangle$ one can define the parameters α or β from Equations (3) or (5), respectively. However, the uncertainties of the thus defined spectral index cannot be straightforwardly calculated, and we performed a Monte Carlo test for each nuclide, characterized by its life (e-folding) time τ. We made N realizations of the time series, where the occurrence of high-fluence ($F > F_0$) events was simulated at each time t using a random-number generator. First, a random number $R(t)$, corresponding to the year t, is picked from

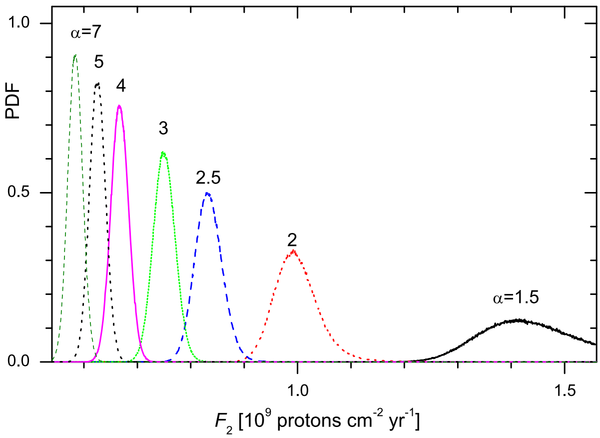


Figure 2 Probability distribution function (PDF) of the values of the average annual fluence (> 30 MeV) F_2 for high-fluence events obtained for 10^6 Monte Carlo realizations for the ^{14}C nuclide using the power-law model (see text). Different curves correspond to different values of the power-law spectral index α, as indicated above each curve.

the uniform distribution between 0 and 1. This random number is then converted into the fluence value $F(t) > F_0$ for the power-law OPDF:

$$R(t) = \int_0^{F(t)} p \cdot \mathrm{d}F = \int_0^{F_0} p \cdot \mathrm{d}F + \int_{F_0}^{F(t)} p \cdot \mathrm{d}F = 1 - P_0\, F_0\, F(t)^{-\alpha}. \tag{6}$$

Thus, if $R \geq (1 - P_0)$,

$$F(t) = F_0 \left(\frac{P_0}{1 - R(t)} \right)^{1/\alpha}. \tag{7}$$

For the exponential OPDF, one can similarly obtain

$$F(t) = F_0 - \frac{1}{\beta} \ln \left(\frac{1 - R(t)}{P_0} \right). \tag{8}$$

The low-fluence ($F \leq F_0$) events were skipped because they are included in the modern statistics $\langle F_1 \rangle$, so that $F = 0$ for $R < (1 - P_0)$. Then the nuclide decay with the lifetime τ was applied so that the mean fluence is defined as

$$F_2 = \frac{1}{\tau} \int_{t=0}^{12\tau} F(t) \cdot \exp(-t/\tau) \cdot \mathrm{d}t, \tag{9}$$

where the integration was performed over 12 lifetimes. As an example, the distribution of the obtained fluence F_2 for a given spectral exponent α (the power-law OPDF) is shown in Figure 2 for ^{14}C, as calculated from $N = 10^6$ simulated series. One can see that the distributions are nearly Gaussian with the mean value corresponding to its mathematical expectation.

Now, the spectral exponent α and its uncertainties can be assessed from the measured fluence F^* for the given nuclide and the above simulations so that

$$F^* - \langle F_1 \rangle = \bigl\langle F_2(\alpha) \bigr\rangle \tag{10}$$

for the mean value of $\langle F_2 \rangle$ and its upper and lower 5 % percentiles. The corresponding calibration curve for the power-law OPDF for ^{14}C is depicted in Figure 3 to define the mean and the upper/lower 5 % percentiles of α from the given value of $\langle F_2 \rangle$.

As an example, we consider the radiocarbon ^{14}C measured in lunar rocks. According to Jull *et al.* (1998), the mean > 30 MeV fluence reconstructed from the ^{14}C lunar record is

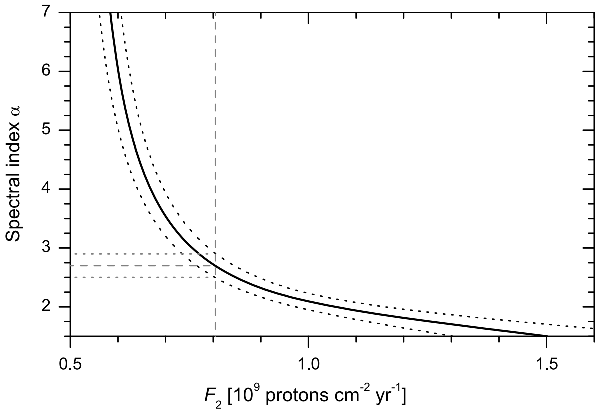


Figure 3 Calibration curve (with its upper and lower 5 % percentiles shown as dotted curves), relating the average annual fluence (> 30 MeV) $\langle F_2 \rangle$ from high-fluence events to the power-law spectral index α of the high-fluence SEP event distribution tail for the ^{14}C nuclide (see text). The gray dashed lines illustrate how the given $\langle F_2 \rangle$ value is converted into the α-values.

$F^* = 1.33 \times 10^9$ protons cm^{-2} yr^{-1}. Considering that $\langle F_1 \rangle = 0.52 \times 10^9$ protons cm^{-2} yr^{-1}, we estimated the high-fluence event contribution as $\langle F_2 \rangle = 0.81 \times 10^9$ protons cm^{-2} yr^{-1}. Using the calibration curve, as illustrated in Figure 3, one obtains that the best-fit power-law exponent is $\alpha = 2.64 \pm 0.21$ within a 90 % confidence interval. This value extends to the sixth column of the first row of Table 1. A similar estimate for the exponential OPDF gives for ^{14}C the spectral index $\beta = (0.328 \pm 0.037) \times 10^{-9}$ cm^2 yr. Similar calculations were made for all other radionuclides for the two OPDF models.

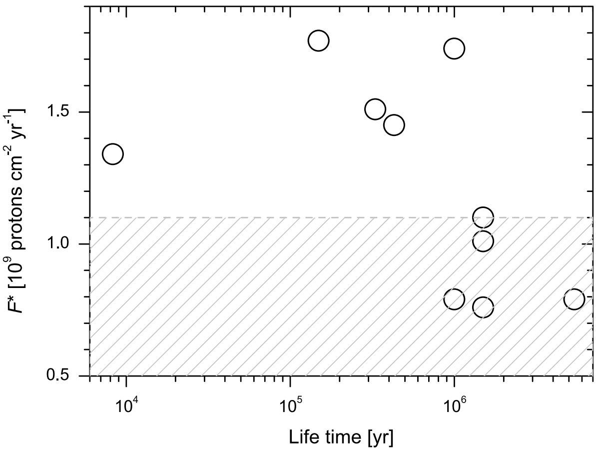
3. Results and Discussion

The results of fitting data from different nuclides are shown in Table 1 for the two considered OPDF shapes—power law and exponential ones. The corresponding distributions are also shown in Figure 1.

All the data from radionuclides with lifetimes shorter than 0.5 Myr (lines 1 – 4 in Table 1) yield reasonable results for the OPDF tail. On the other hand, as we now show, the values of $F^* < 1.1 \times 10^9$ protons cm^{-2} yr^{-1} cannot be fitted by either model. The relation between the estimated fluence and the lifetime is shown in Figure 4. Most long-living nuclides, except for the ^{26}Al-based estimate by Grismore *et al.* (2001), yield a low fluence, lower than the recent measurements (shown as the gray dashed line). In fact, these data cannot be consistent with the present model. This covers most of the data related to long-living nuclides (lines 5 – 11 in Table 1).

The discrepancy between the results based on short- ($\tau < 0.5$ My) and long- ($\tau = 1 - 5$ Myr) living nuclides cannot be ascribed to the difference between the measured samples of lunar rocks, because some of the data were obtained from the same samples (see Table 3 in Nishiizumi *et al.*, 2009). Thus, this discrepancy is systematic and can be interpreted in different ways. One is that the SEP fluence was as high as during modern times for the past 0.5 Myr, but was significantly and systematically lower before that. However, this would imply a dramatic and sharp transition by a factor greater than 2 – 3 between the two modes to occur at about one Myr ago, which sounds unrealistic (Nishiizumi *et al.*, 2009). Another option is a systematic error in the evaluation of the SEP fluence from lunar samples that is accumulated over time, leading to an underestimate of the fluence in the far past. However, studying this type of uncertainties, *e.g.*, correction for erosion or better nuclear cross-sections used in the modeling, is beyond the scope of this work. Accordingly,

Figure 4 The measured averaged fluences of protons (>30 MeV) F^* as a function of the nuclide lifetime (see Table 1). The hatched area corresponds to the averaged fluence F^*, which is inconsistent with the measurements of 1955 – 2007 and cannot be fit by the model.



we consider only shorter-living ($\tau < 0.5$ Myr) radionuclides here, stating that OPDF cannot be evaluated from long-living nuclide data.

Next we compared the OPDF obtained from terrestrial cosmogenic radionuclides (Usoskin and Kovaltsov, 2012) with those presented here for lunar samples. The comparison is shown in Figure 1. For the power-law OPDF tail (Figure 1a) one can see that only the ^{14}C-based lunar results are barely consistent with the terrestrial data. The data based on the lunar ^{14}C (line 1 in Table 1) imply in the framework of the power-law OPDF that events with a fluence $>50 \times 10^9$ protons cm^{-2} yr^{-1} would have occurred on average every 5000 yr. Thus, a few such events would have occurred during the Holocene, each stronger than the greatest observed event of AD775 (Miyake *et al.*, 2012; Usoskin *et al.*, 2013). However, strong events like this cannot have been missed in the terrestrial radionuclide data (Usoskin and Kovaltsov, 2012), and the probability that purely randomly no such events occur during the eleven millennia of the Holocene is about 0.11. On the other hand, a simple χ^2-test suggests that this OPDF tail does not fit the terrestrial radionuclide data (open symbols) at a significance level of 0.01. Thus, the null hypothesis is rejected and this OPDF tail is considered to be inconsistent with the terrestrial cosmogenic radionuclide data. We note that the effective timescale covered by ^{14}C in lunar rocks coincides with the Holocene, and thus this data set can be directly compared with terrestrial data. All other lunar-based radionuclides obviously contradict the terrestrial data. Namely, the data based on lunar ^{36}Cl (line 4 in Table 1) imply that events with $F^* > 50 \times 10^9$ protons cm^{-2} yr^{-1} would have occurred on average every 1500 yr. This leads to a probability of $\approx 10^{-3}$ that purely randomly no events occurred during the Holocene. Thus, the power-law OPDF tail is inconsistent with the terrestrial cosmogenic nuclide data at a level of 10^{-3}. Other results (lines 3, 4, and 5) overestimate the OPDF even more. The too-steep power-law tail implied by the ^{10}Be/^{26}Al ratio (line 7 in Table 1) is also inconsistent with the observed data, but heavily underestimates the OPDF. We conclude that the power-law shape of the OPDF tail disagrees with the terrestrial data.

On the other hand, a similar analysis of the exponential shape of the OPDF (Figure 1b) suggests that the result for ^{14}C (line 1 of Table 1) is well consistent with the terrestrial data. The null hypothesis that this tail is the same as the measured OPDF for terrestrial cosmogenic nuclide data cannot be rejected (the significance level is 0.26). The other exponential tails, while giving a formally poorer fit, still agree reasonably well with the terrestrial data.

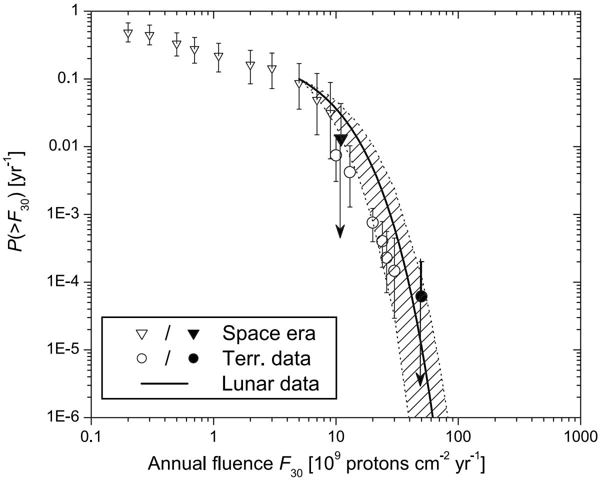


Figure 5 The cumulative occurrence probability distribution of strong SEP events—a combined plot for timescales from years to a million years. Triangles represent observations of the space era. Circles represent data obtained from terrestrial cosmogenic radionuclide data (Usoskin and Kovaltsov, 2012). Filled symbols correspond to the upper limits based on the fact that no events stronger than the given fluence value have been observed. The solid curve with the hatched range (90 % confidence interval) is the best-fit estimate (this work) based on cosmogenic radionuclides with lifetimes shorter than 0.5 Myr measured on lunar samples.

Because estimates based on individual radionuclides differ quite a bit from each other and because they are somewhat uncertain, we also provide a combined estimate of the OPDF for all nuclides with lifetimes shorter than 0.5 Myr (*viz.* lines 1 – 4 in Table 1). The mean value of F^* is 1.51 ± 0.18 ($\times 10^9$ protons cm^{-2} yr^{-1}) for the 90 % confidence interval. We considered only the exponential-tail model since the power-law does not fit the terrestrial data, as described above (*cf.* Nymmik, 1999). The corresponding spectral index is found to be $\beta = 0.202^{+0.122}_{-0.053}$ (10^{-9} cm^2 yr). This best-fit OPDF is shown in Figure 5 as the solid curve with the hatched range. One can see that all three timescales considered, *viz.* years-decades measured during the space era, centennia-millennia from terrestrial radionuclides, and the scale of up to a million years, are consistent in the OPDF. They indicate a strong exponential roll-over for strong SEP events that is theoretically expected because of the effects of the wave-particle interactions, which lead to the streaming limit of fluxes observed by space-borne instruments during strong SEP events (Reames, 2004).

4. Conclusions

We have assessed the occurrence probability distribution function for strong SEP events whose fluence of > 30 MeV protons exceeds 5×10^9 (protons cm^{-2} yr^{-1}), from data of different cosmogenic radionuclides measured in lunar samples. We presented in Figure 5 a combined cumulative occurrence probability distribution of SEP events based on three timescales: directly measured SEP fluences for the past 60 years, estimates based on terrestrial cosmogenic radionuclides ^{10}Be and ^{14}C for the multi-millennial (Holocene) timescale, and cosmogenic radionuclides measured in lunar rocks on a timescale of up to 1 Myr. All three timescales yield a consistent distribution.

We conclude the following:

- All SEP fluences estimated for long-living isotopes with a lifetime longer than 1 Myr in lunar rocks are inconsistent with the terrestrial data on decadal to multi-millennial timescale. Accordingly, the average SEP fluences cannot be reliably assessed on a timescale longer than 1 Myr.
- The data suggest a strong roll-over of the occurrence probability so that the SEP events with an F_{30} fluence greater than 10^{11} protons $\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ are not expected on a Myr timescale.
- The best-fit result for the exponential tail of the occurrence probability distribution function [Equation (4)] yields a value of β in the range of $0.15-0.32$ ($\times 10^9$ cm^2 yr).

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