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Consistency of the average flux of solar energetic particles over different timescales up to mega-years

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Fluxes of solar energetic particles (SEPs) produced during solar eruptive events such as flares or coronal mass ejections are directly measured by space-borne detectors over the past decades. However, rare (about once per millennium) extreme SEP events have been recently discovered as studied by terrestrial cosmogenic proxy data for the past ten millennia. In addition, isotopic analysis of lunar rocks can reveal the average SEP fluxes on the mega-year timescale. Until now, it was unclear whether the SEP fluxes averaged over different timescales are mutually consistent. These different datasets are analyzed here to study their mutual consistency. Using the data from directly measured SEPs and reconstructions of extreme SEP events, we built a joint probability distribution function of the occurrence of SEP annual integral fluxes in the energy range between 30 and 200 MeV on different timescales. Based on that, the expected long-time averaged SEP flux was computed and directly compared to the lunar data representing the mega-year SEP flux. The results imply that contrary to the earlier assumptions, the SEP fluxes directly measured during the recent decades are not representative of the long-term averaged SEP flux as they compose only 20 – 55 % of it. A major fraction of the mega-year averaged SEP flux is formed by rare but extremely strong SEP events. It is shown that the combined statistics of all three different datasets and timescales (decadal direct data, millennial cosmogenic proxy data and mega-year lunar data) are fully consistent, implying that our knowledge of the whole range of the SEP fluxes, from frequent weak events to rare extreme ones, is likely complete now.

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1. Introduction

The low-energy part, with the kinetic energy of < 100 MeV, of the energetic-particle intensity near Earth is dominated by solar energetic particles (SEPs) [1]. The flux of SEPs is highly variable by many orders of magnitude and not always present near Earth which makes it difficult to evaluate the average SEPs flux over a long time scale. Because of the high intensity of SEPs, these particles form a strong radiation field in space beyond shielding by the Earth's atmosphere or the geomagnetic field [2]. It is important, from both theoretical and practical points of view, to know the average SEP flux and its variability at different timescales.

There are three ways to study the mean SEP flux using direct measurements and indirect proxy [3], as described in the subsequent sections. Here we describe the estimates of the average SEP fluxes on decadal (Section 2), multi-millennial (Section 3) and millions-of-years (Section 4) timescales, and then make an intercomparison between them in Section 5. Conclusions are summarized in Section 6.

2. In-situ measurements during the past decades

SEPs are measured in space since the advent of the Space era in the 1960s, however, earlier data were somewhat uncertain because of a problematic inter-calibration between instruments of different types. Since 1984, consistent measurements by the GOES (Geostationary Operational Environmental Satellites) family are made on a geostationary orbit. This series has been recently carefully re-calibrated and homogenized [4] and provides an accurate dataset of SEP fluxes with energy ranges in the deca- to hecto-MeV range. The flux of SEPs is highly variable from year to year being high during the years of the solar activity maxima and nearly absent during the minimum years. This is illustrated in Figure 1 for the annual F_{30} fluence (annually integrated flux of protons with energy above 30 MeV). The fluence for the active years is mostly defined by the strongest SEP events while a large number of weaker events does not contribute significantly. An example of the cumulative complementary occurrence distribution of the years with given annual fluence F_{200} is shown as blue dots in Figure 2.

The SEP flux averaged over a solar cycle changes significantly, from $\langle F_{30} \rangle \approx 7$ cm^{-2} s^{-1} for solar cycle 24 to ≈ 50 cm^{-2} s^{-1} for cycle 23. It is important that the most recent cycles 24 and 25 are typical for long-term solar activity [5, 6], while solar cycles 22 and 23 were unusually high corresponding to the Modern grand maximum of solar activity [7]. It is likely that the mean flux of SEPs during the last solar cycle is typical for the Sun in contrast to that averaged over the previous decades characterized by a very high solar activity. Accordingly, we consider here the average energy spectrum of SEPs in the energy range from 30 to 200 MeV, obtained for the last solar cycle 24, as depicted in Figure 3.

However as discussed below, direct observations over the past decades do not cover the entire range of possible SEP fluxes [3] and can be considered only as a lower limit for that.

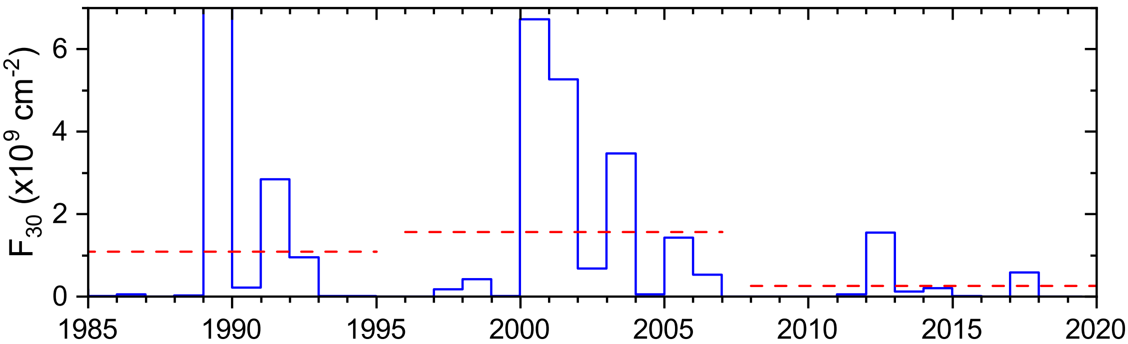

Figure 1: Annual fluence of SEPs with energy above 30 MeV, F_{30}, for 1984 – 2019 [4]. Red dashed lines depict the F_{30} fluences averaged over individual solar cycles.

3. Cosmogenic isotopes in terrestrial natural archives as a proxy to extreme solar particle events

Although energetic particles cannot be measured directly before the advent of the Space era, they can be studied in the past using the method of cosmogenic isotopes. The method is based on measurements of radioactive cosmogenic isotopes, such as ^{14}C, ^{10}Be and ^{36}Cl, which are produced by energetic particles in the Earth's atmosphere [8]. Upon production, the isotopes are redistributed in the terrestrial system and stored in natural stratified archives such as tree trunks, polar ice cores, marine or lake sediments, etc. Measurements of the natural archives are performed in modern laboratories and are, thus, of nearly homogeneous quality. This method is primarily used to study long-term solar variability via the modulation of galactic cosmic rays [6], but it has been recently discovered [9] that extremely strong SEP events can leave measurable signatures in the cosmogenic isotope records [10, 11]. Using different cosmogenic isotopes with different production yields depending on the energy of the primary energetic particles impinging on the atmosphere, the energy (or rigidity) spectrum of SEPs can be estimated [e.g., 12, 13].

Using this method, several extreme SEP events have been discovered in cosmogenic isotopes throughout twelve millennia of the Holocene, viz. the present inter-glacial epoch [11], with the mean occurrence rate of one event per 1500 – 2000 years. At present, five confirmed events (7176 BCE, 5259 BCE, 660 BCE, 774 CE, 993 CE), as well as three candidates yet to be confirmed (5410 BCE, 1052 CE and 1279 CE), are identified [11]. All these events were several orders of magnitude stronger than even the strongest SEP events known for the past decades.

Accordingly, these extreme SEP events may contribute to the long-term average SEP flux since, while being very rare, they are extremely strong.

4. Cosmogenic isotopes in lunar rocks as a proxy for the long-term-averaged SEP flux

Another direct method to reconstruct SEP flux on the very long-term timescale is related to cosmogenic isotopes produced and preserved in lunar rocks. Since the Moon is not protected by the atmosphere or its own magnetic field, its surface is open to all kinds of radiation including

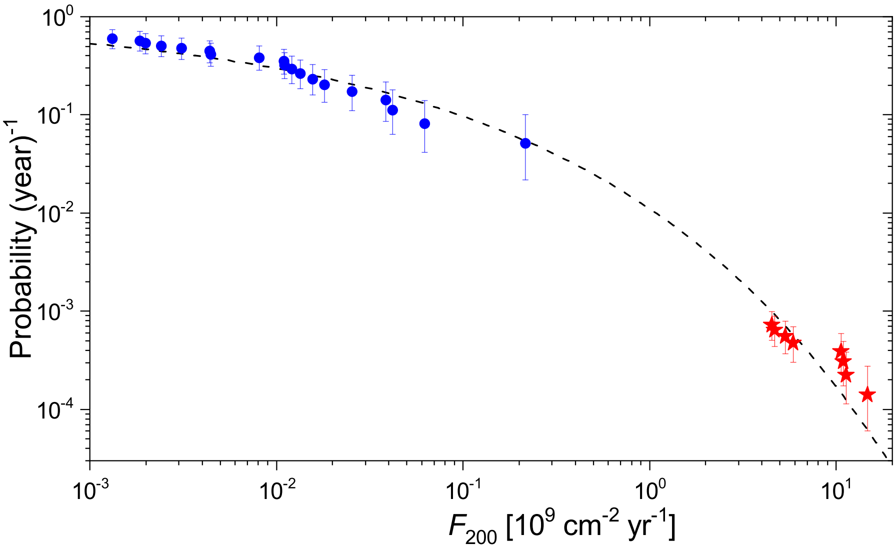

Figure 2: Cumulative complementary occurrence probability of a year with the annual fluence F_{200} of SEPs with energy above 200 MeV exceeding the given value. Blue dots correspond to the directly measured data for the last decades [4], while red stars denote the reconstructions for the extreme SEP events based on cosmogenic isotopes [13]. The dashed curve presents the best-fit Weibull distribution [6].

low-energy charged particles such as SEPs which produce isotopes directly in the lunar soil or rocks. Many lunar samples were brought to Earth by the Apollo missions in the 1970s and analyzed for their contents. Using long-living isotopes such as ^{26}Al, the mean flux of SEPs over a mega-year timescale was estimated (see, e.g., [14]). The timescale at which the averaged flux is obtained is defined by the lifetime of the isotope, which is about 717 kiloyears for ^{26}Al. No time resolution can be achieved with the lunar data but a spectrum of the energetic particles can be roughly estimated because the depth at which the cosmogenic isotopes were produced in lunar samples depends on the energy of particles.

5. Consistency of SEP flux at different timescales

Here we compare SEP fluxes average at different timescales as depicted in Figure 3 [cf. 3].

On one hand, as seen from the Figure, the average flux of SEPs measured during the recent solar cycle 24 (blue dots) is systematically lower, being only 20 – 55 % of the estimates based on cosmogenic isotopes in lunar rocks (green squares). Earlier discussions [e.g., 14–16] proposed that the mega-year-averaged SEP flux is generally consistent with the results of the direct SEP measurements during solar cycles 21 – 22 which were characteristic of the Modern grand maximum of solar activity [7]. However, the more typical SEP flux for solar cycle 24 is too weak to match the mega-year estimates.

On the other hand, when the statistics of the known extreme solar particle events is added to that of the direct measurements (as shown in Figure 2), the average SEP flux (red stars in Figure 3) appears stably consistent, within the uncertainties, with the estimates based on the cosmogenic isotopes measured in lunar rocks. This suggests that the contribution of extreme solar particle

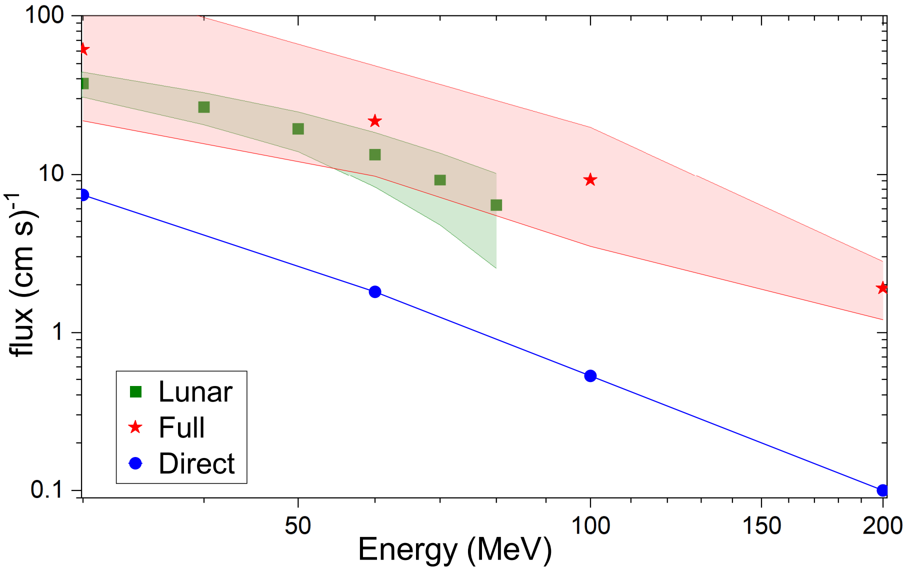

Figure 3: Comparison of averaged fluxes of SEPs in the energy range between 30 and 200 MeV as estimated from different data sources: Direct (blue dots) – direct in-situ SEP measurements for the solar cycle 24; Full (red stars with the pink-shaded 1σ uncertainties) – an estimate based on the joint distribution of direct and proxy-based data sets (see Figure 2); Lunar (green squares with the green-shaded full-range uncertainties) – reconstructions of the mega-year SEP flux based on lunar data [14].

events, which appear very seldom (roughly once per millennium) but are extremely strong (several orders of magnitude stronger than 'normal' SEP events), to the long-term average SEP flux, is major. It forms more than half of the mega-year-averaged SEP flux and cannot be neglected contrary to what was assumed previously.

The three datasets representing different timescales and experimental methods are found to be mutually consistent implying that our knowledge of the range of SEP events is complete.

6. Conclusions

A comparison between averaged SEP fluxes over different timescales from decades to a million of years reveals that:

- The average particle flux from 'normal' SEP events directly measured during the recent solar cycle 24 was too weak, by a factor of two – four, with respect to that averaged over the last million years.
- Extreme SEP events known from cosmogenic isotopes in terrestrial archives form at least half of the very long-term averaged SEP flux.
- When the statistics of both 'normal' and extreme SEP events are merged together, their combined averaged flux is fully consistent, within the uncertainties, with the mega-year-averaged one.

- Thus, different pieces of the puzzle match together implying that we are unlikely to miss an important contributor to the average SEP flux.

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