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Strongest directly observed Solar Proton Event of 23-Feb-1956: Revised reference for the cosmogenic-isotope method

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Solar extreme solar proton events (SPEs) form important radiation hazards for modern technological society. The strongest directly observed SPE took place on 23-Feb-1956 as an up to 5000 % increase of the count rate of ground-based neutron monitors. It was characterized by a very hard energy spectrum and strong particle fluence. On the other hand, as known from indirect proxies (cosmogenic isotopes), several extreme events, one – two orders of magnitude stronger, occurred during the past millennia. In order to study past events, a reference scale needs to be made. The SPE of 23-Feb-1956 is often used as such a reference. Thanks to the recent developments in the methodology of SPE analysis, the spectrum of fluence of the reference event have been revisited and re-assessed with higher precision. Here we present an estimate the sensitivity of the cosmogenic-isotope method to detect extreme SPEs in the past. It is shown that the modern accuracy of the cosmogenic-isotope method to SPEs is insufficient, by an order of magnitude for any single isotope record, to detect the reference event but can resolve events a factor 3 – 4 stronger using a multi-proxy method. This provides a solid basis for research in the field of extreme events, both for fundamental science, namely solar and stellar physics, and practical applications, such as the risk assessments of severe space-based hazards for a modern technological society.

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1. Introduction

First instrumental detection of solar energetic particles (SEPs) was made about 80 years ago using ground-based ionization chambers [1], and the SEP events were studied using both ground-based neutron monitors (NMs) since the 1950s and space-borne instruments since the 1970s [2]. While SEP events are quite often (except for the solar cycle minimum), they are mostly relatively weak with a soft energy spectrum. However, stronger and harder SEP events may occur occasionally, called GLE (Ground Level Enhancement), where the energy of particles can be sufficiently high (greater than several hundred MeV) to initiate the atmospheric cascade whose secondaries can be detected on the ground by NMs (see the list at https://gle.oulu.fi). The strongest directly observed GLE#5 took place on 23-Feb-1956 with a ≈x50 enhancement (over the background level) during several hours [3]. Statistic of the directly known SEP/GLE events have been analysed (e.g., [4]) but the question about extreme solar events is still open – what is the maximum strength of SEPs and how often can they occur (e.g., [5–7])? Recently, such extreme SEP events have been discovered for the last millennia using a proxy method of cosmogenic isotopes [8]. The strongest known event took place in 774 AD [9, 10] and it was a factor 40 – 100 stronger than the GLE#5. Later, several more SEP events were found for the last millennia using the cosmogenic-isotope method (see Table 1).

One can see that all events found using cosmogenic-isotope data are one–two orders of magnitude stronger than the strongest event of the instrumental era. Can somewhat weaker events be detected in the past to provide sufficient statistic? This question was studied earlier (e.g., [11]) and more recently [12]. Here we develop such an analysis using an updated methodology.

Table 1: The relative strength (in the sense of the given isotope production) for known extreme SEP events in the past with respect to the GLE#5 (23-Feb-1956), R_{1956}. Values are adopted from [8, 13–15].

Event	774 AD	660 BC	994 AD	1279 AD†	1052 AD†
R_{1956}	70 ± 30	50 ± 25	37 ± 17	30 ± 14	24 ± 11

† not yet confirmed.

2. Cosmogenic isotope production

Cosmogenic isotopes are produced as a result of nuclear reactions induced by energetic particles in the Earth's atmosphere [16]. Most important are ^{14}C, which is a result of (n, p) reactions, and ^{10}Be and ^{36}Cl produced in spallation reactions. The yield-function (number of isotopes produced by the unit flux of energetic particles with fixed energy impinging on the top of the polar atmosphere) have been recently computed with the highest presently-possible precision [17]. After production, the isotopes are subjected to transport in the atmosphere and deposition in natural archives (tree trunks or polar ice sheets) where they can later be measured and serve as a proxy for cosmic-ray flux variability [18]. By combining a parameterized transport model with the production model, one can obtain the effective yield function, which makes it possible to relate the cosmic-ray flux directly to the measured content of the isotope in a natural archive [19]. Here we assumed that ^{14}C is globally mixed in the atmosphere, while for ^{10}Be and ^{36}Cl, a parameterized model [20] was used.

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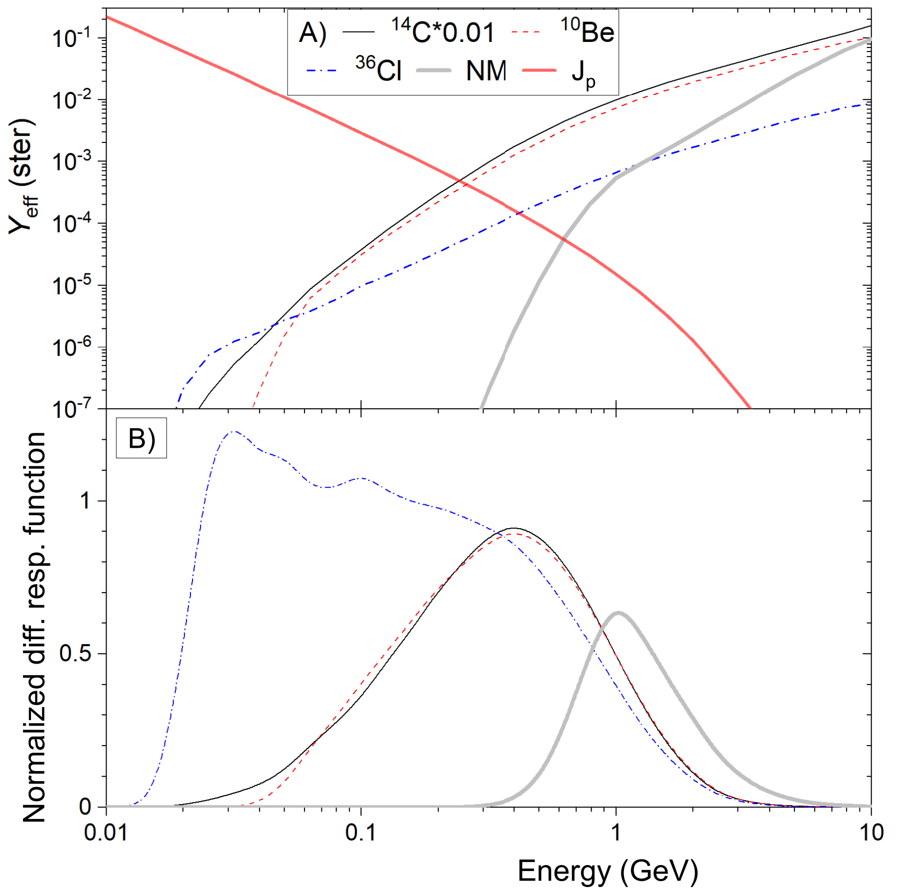

Figure 1: A) Effective yield functions Y_{eff} for ^{14}C (scaled down by a factor of 100), ^{10}Be and ^{36}Cl as well as for a polar sea-level 6NM64. The red solid line depict the differential energy spectrum J_p of GLE#5 in arbitrary units [22]. B) Normalized (per unity integral) differential response functions (see text) for the GLE#5.

The effective yield functions Y_{eff} are shown in Figure 1A along with the yield function of a polar sea-level NM [21]. One can see that cosmogenic isotopes are more sensitive to lower-energy (<1 GeV) particles than a NM. Sensitivity of ^{14}C and ^{10}Be are nearly identical in shape although the total yield of ^{14}C is two orders of magnitude higher. On the other hand, ^{36}Cl is more sensitive to low-energy (<100 MeV) cosmic rays than other isotopes.

A product of the effective yield function and the energy spectrum J_{p} makes the differential response function $S(E) = Y_{\text{eff}}(E) \cdot J_{\text{p}}(E)$, so that an integral of S over energy gives the total yield of the isotope (or counts of a NM). The normalized (so that the integral is equal to unity) differential response functions are shown in Figure 1B. One can see that the main contribution to ^{3}6Cl production and deposition is made by SEPs with energy below 100 MeV, with the peak sensitivity being at about 30 MeV. On the other hand, the peak of both ^{10}Be and ^{14}C isotopes corresponds to about 400 MeV. This makes it possible to assess the spectral shape of extreme SEP events using different isotopes [13]. For comparison, $S(E)$ is shown also for a polar NM that peaks at about 1 GeV.

Table 2: Production (in atoms per cm^2) of cosmogenic isotopes by SEPs for global mixing for ^{14}C and polar ice (as parameterized by the model [23]). Production by the reference GLE#5 is shown in the upper line. Production by the strongest known historical SPE of 775 AD and its ratio R_{1956} to that of GLE#5 are shown in the middle block. The annual production rate due to GCR for the conditions of 775 AD (ϕ = 450 MV [24], VADM=10^{22} A m^2 and the sensitivity (in multiples of the GLE#5) of the cosmogenic isotope method to detect an SEP event are shown in the bottom block.

Isotope	^{14}C (global)	^{10}Be (polar ice)	^{36}Cl (polar ice)
GLE#5 (23-Feb-1956)	$2.72 \cdot 10^6$	$2.05 \cdot 10^4$	$2.34 \cdot 10^3$
775 AD	$1.88 \cdot 10^8$ [25]	$9.27 \cdot 10^5$ [13]	$3.15 \cdot 10^5$ [13]
R_{1956}	69	45	135
GCR (775 AD)	$5.2 \cdot 10^7$	$3.3 \cdot 10^5$	$2.9 \cdot 10^4$
Sensitivity	19	16	12

3. Strongest SEP event, GLE#5 of 23-Feb-1956 as a reference

The strongest SEP event of the instrumental era took place on 23-Feb-1956 as a huge enhancement of the count rate of ground-based NMs (>5000 %·hr for Ottawa NM [3]). It was characterised by a very hard (hardest known) SEP spectrum which serves as a reference for the past extreme events [12, 13]. The differential energy spectrum (arbitrary scaled) is shown in Figure 1A.

By integrating the differential response function S over energy one can calculate the expected signal (enhancement over the GCR background) of cosmogenic isotopes caused by the SEP event. These values are shown in the upper block of Table 2. One can see that the amount of atoms of ^{14}C per cm^2 produced by the GLE#5 is two–three orders of magnitude than that of other isotopes. For a comparison, the middle block shows the estimated production for the SEP event of 775 AD, and the ratio between them. The 775 AD event appears roughly two orders of magnitude stronger in the isotope production than GLE#5 and is clearly seen in the data [10, 13].

Theoretically computed annual production/deposition of the isotopes by GCR (for the conditions corresponding to the 775 AD, viz. the modulation potential ϕ = 450 MV [24] and the geomagnetic dipole moment VADM=10^{23} A m^2 [26], are shown in the bottom block of Table 2. The cosmogenic-isotope production by the GLE#5 corresponds to roughly a monthly production of the isotopes by GCR, which cannot be resolved in annual datasets. We note that the annual production of GCR can roughly represent the sensitivity of the cosmogenic isotope method, considering both the measurement errors, uncertainties of transport and the variability of the data for a single dataset (cf. [12]). The bottom line of Table 2 provides the scaling ratio of the strength the GLE#5 should have to reach this detection limit. It appears that an order-of-magnitude stronger SEP event is needed to leave a statistically recognized signature in cosmogenic isotope records. However, the use of multiple data series may reduce the uncertainty and thus the detection limit, approximately as square root of the number of independent datasets.

4. Conclusions

The GLE#5 event (23-Feb-1956) was the strongest one of the instrumental era and had the hardest known spectrum SPEs. Yet, it was too weak to produce a detectable signature in cosmogenic

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isotopes such as ^{14}C, ^{10}Be and ^{36}Cl. On the other hand, several extreme SEP events are known over the past millennia in the cosmogenic-isotope records, implying than orders-of-magnitude SEP events can be produced by the Sun. For those events we only know that their energy spectra were relatively hard and assume that GLE#5 can serve as a reference event.

Here we compute production of the cosmogenic isotopes by SEPs during GLE#5 and estimate the detection limit of extreme SEPs. We show that the sensitivity of the cosmogenic-isotope method to SEP events is by an-order-of-magnitude too low to detect the GLE#5 event, thus forming an observational gap between the modern instrumental data and the proxy-based methods in the past. On the other hand, the use of multiple independent proxy records, preferably from different locations (for example, Greenland and Antarctica for ice cores) and different isotopes, to exclude or minimize the influence of regional climate conditions, can reduce the uncertainties of the cosmogenic-isotope method and enhance its sensitivity by a factor of two–three. Although this is still not sufficient to reach the level of modern events, it can reduce the gap to a factor of three.

Thus, with the use of multiple records and improved methodology of cosmogenic isotope measurements, we expect that more strong SEP events to be found in the past records, reducing the observational gap and allowing for a better assessments of the strength and occurrence probability of extreme solar events, and subsequently improving our awareness of the related hazards and risks.

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