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Reconstruction of the fluence of extreme solar particle events registered in cosmogenic proxies

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Extreme solar particle events (ESPEs) are infrequent yet highly potent manifestations of solar activity. These events result in the production of significant amounts of cosmogenic isotopes (CIs): ^{10}Be, ^{36}Cl, and ^{14}C, which are subsequently deposited in natural stratified archives. Analyzing CI measurements from these archives allows us to assess the particle fluxes during ESPEs. In this study, we introduce a novel approach to reconstruct ESPE fluence (integral flux) by using recent modelling advancements. This method enables the integration of diverse CI data within a single comprehensive model. Within the new approach, ESPE fluence is represented as an ensemble of scaled fluence reconstructions for ground-level enhancement (GLE) events, detected by the neutron monitor network since 1956 and coupled with satellite and ionospheric measurements. The reconstructed ESPE fluences exhibit a softer spectral shape compared to previous estimates, leading to significantly higher estimates of the low-energy (E <100 MeV) fluence. Consequently, ESPEs pose an even greater risk to modern technological systems than previously believed. To facilitate broader applications, the reconstructed ESPE fluences are fitted using a modified Band function which simplifies the utilization of the obtained results in various practical contexts.

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1. Introduction

Cosmogenic isotopes (CIs) provide a quantitative means to study solar and cosmic-ray variabilities over long timescales [1, 2]. These isotopes, such as ^{14}C, ^{10}Be, and ^{36}Cl, are produced by cosmic rays in the Earth's atmosphere and stored in independently dateable stratified archives like tree rings and ice cores. They serve as valuable proxies for long-term solar activity reconstructions [3–6]. While sporadic solar energetic particle (SEP) events have negligible impact on CI production, rare and intense extreme solar particle events (ESPEs) can generate huge amounts of CIs which will be detectable over the galactic cosmic ray (GCR) background [7–9].

ESPEs represent a unique type of solar eruptive event that has not been directly observed with scientific instruments. Understanding their characteristic parameters, particularly the energy spectrum, is crucial. The energy spectrum can be estimated by analyzing multiple isotopes for the same ESPE event, because ^{14}C and ^{10}Be are sensitive to SEPs with energies above 230 MeV, while ^{36}Cl is sensitive to lower energies of about 60 MeV [10].

Several approaches have been employed to evaluate the spectra of ESPEs. In particular, some studies [8] have utilized the relationship between the ^{36}Cl/^{10}Be ratio and the spectral hardness of SEP-induced ground level enhancements (GLEs) registered by the neutron monitor (NM) network. By comparing measured CI concentrations with modelled production rates induced by modern GLEs, these studies estimated the spectra of ESPEs.

In this work, we present a systematic reconstruction of integral fluences for four ESPEs: 994 CE, 775 CE, 660 BCE, and 7176 BCE. Our approach involves a simulation of CI production during the GLE events, scaling the simulated GLE CI response to fit all three CI data and using obtained scaling for the reconstruction of ESPE fluence. This new method enhances the accuracy of ESPE fluence reconstruction and provides insights into the energy spectra of ESPEs. These proceedings shortly describe the main ideas of the full paper, which was published in 2023 [11].

2. Data and analysis

We utilize two data sources to study SEP events: cosmogenic isotope data for ESPEs over the past millennia and direct observations of SEP events in recent decades through spacecraft and NM observations of GLEs.

We analyze data for cosmogenic isotopes ^{10}Be, ^{14}C, and ^{36}Cl from four ESPEs: 7176 BCE, 660 BCE, 775 CE, and 994 CE. These isotopes are extracted from independently dated stratified archives such as tree rings and polar ice cores. To assess the ESPE isotope production, we calculate the excess production rate $Q_{\rm ESPE}$ by subtracting the background production rate $Q_{\rm GCR}$ caused by galactic cosmic rays (GCRs). However, the transport and deposition processes for ^{10}Be and ^{36}Cl [12] introduce uncertainties due to local/regional effects. To address this, a scaling factor k, typically ranging from 0.8 to 1.3 [13], is typically introduced to account for the discrepancy between modelled and measured production rates. This factor is a free parameter and affects the conversion between production rates and SEP spectra. To mitigate this uncertainty, we employ the peak factor $P_{\rm ESPE}$, defined as the ratio of the measured isotope's production/deposition excess $Q_{\rm ESPE}$ to the background annual production/deposition rate $Q_{\rm GCR}$, as an index of ESPE strength. In this study, we use the P-values for ^{10}Be and ^{36}Cl and convert published Q_{ESPE}-values to P-values for ^{14}C during the fluence reconstruction procedure.

Spacecraft measurements have directly captured thousands of SEP events in recent decades [14, 15]. However, only a few dozen of these events have been energetic enough to generate a nucleonic cascade in the Earth's atmosphere and potentially produce cosmogenic isotopes. Despite the large number of directly observed SEP events over the past 70 years, they have not led to a detectable amount of cosmogenic isotopes [16, 17]. The strongest SEP events, known as GLEs, have been detected by ground-based NMs and serve as reference events for ESPEs [17, 18]. Recently, Koldobskiy et al. 2021 [19] reconstructed SEP spectral fluences for 58 moderate and strong GLE events using a combination of ground-based and space-borne datasets and this dataset (represented by parameterization with the modified Band function, MBF) is used in this work. The CI method cannot distinguish between a single extreme event and a series of consecutive events, as in the case of October–November 1989 GLEs. To address this, we combine "serial" GLEs produced by the same solar active region into pseudo-single GLE events with summed spectral fluences.

To compare with the measured ESPE data, we used a model based on yield functions [20] to compute the production of CIs in the Earth's atmosphere. For radiocarbon (^{14}C), which is globally mixed in the atmosphere, we used a multi-box model to simulate its global carbon cycle [21]. For ^{10}Be and ^{36}Cl, we considered their concentrations in ice, which were translated into depositional fluxes using a parameterized approach that accounts for transport and deposition [12, 22]. We constructed "effective" yield functions, which include CI production and transport/deposition. The production of cosmogenic isotopes from galactic cosmic rays (GCRs) was modelled using the force-field approximation [23] and the local interstellar spectrum of GCRs by Vos et al., 2015 [24]. We also considered heavier nuclei using an approach described in Koldobskiy et al., 2019 [25]. The modulation potential ϕ, which accounts for the modulation of GCRs by the heliospheric and geomagnetic fields, was taken into account using values corresponding to the times of the extreme events [13, 26, 27]. To account for the geomagnetic shielding, we considered two archeo/paleomagnetic reconstructions of the geomagnetic field: one by Knudsen et al., 2008 [28] and another by Panovska et al., 2018 [29]. Using the effective yield functions, the production of cosmic rays from GCRs and SEPs was calculated for the GLE events described above. After that, we fitted the ensemble of obtained CI responses to fit the observable CI data. Obtained scaling factors were used to construct an ensemble of scaled fluences, which serve as an estimate for ESPE fluence. More detailed description of this approach is given elsewhere [11].

3. Discussion

Figure 1 compares our results with earlier spectral estimates for ESPEs of 994 CE, 775 CE, 660 BCE, and 7176 BCE. Our new spectral reconstruction shows a significantly softer spectrum at E >100 MeV compared to the previous estimates by Mekhaldi et al., 2015 [8]. This is because the earlier work relied on a simplified assumption of an unrealistically-hard power-law shape of the SEP spectrum [31]. In addition, the yield function of CI production has been revised recently [20], resulting in a higher enhancement factor needed to explain past ESPEs. In Mekhaldi et al., 2021 [17], the fluence >30 MeV for the 775 CE and 994 CE events was reevaluated using more realistic fluence spectra [32] and accounting for solar modulation [33, 34], which brought the estimates

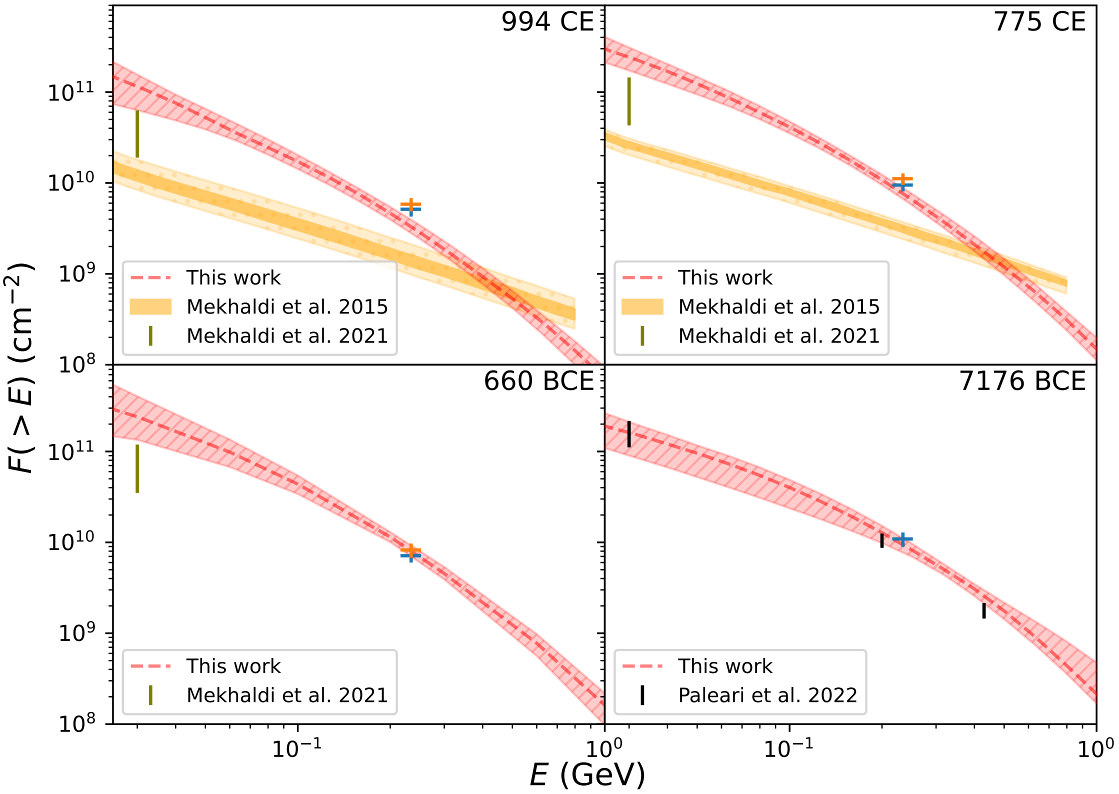

Figure 1: Integral fluences of ESPEs of 994 CE, 775 CE, 660 BCE and 7176 BCE: red dashed lines with shaded areas depict the reconstructions presented here; orange lines with shaded areas depict the spectral reconstructions by Mekhaldi et al., 2015 [8]; olive vertical bars represent estimates of the F_{30} fluence by Mekhaldi et al., 2021 [17]; black vertical bars for 7176 BCE correspond to the spectral estimates by Paleari et al., 2022 [30] for the ESPE of 7176 BCE. Results of single-proxy "effective energy" fluence reconstruction method [10] for ^{14}C data are also shown by colour crosses for comparison.

closer to our new reconstruction but still significantly lower. The difference can be attributed to the use of scaled spectra from specific GLEs in the earlier work, while the new reconstruction is based on a broader ensemble of GLEs [19]. Fluence reconstruction for ESPE 7176 BCE is in good agreement with the results of Paleari et al., 2022 [30], who used a similar approach. The events of 775 CE, 660 BCE, and 7176 BCE show close similarities within the uncertainties, while the 994 CE event is 2–3 times weaker. Comparing these spectra with those of typical GLEs, it is evident that the ESPE spectra are about two orders of magnitude higher. The good fit between the CI data and scaled spectra of observed GLEs suggests that the physical mechanisms of acceleration and interplanetary transport during ESPEs are similar to those of normal GLEs, supporting the hypothesis that ESPEs are "Black swan" rather than "Dragon king" events [6, 35].

To facilitate various applications, such as the calculation of cosmogenic isotope responses, we parameterized the differential-in-energy particle flux using the MBF spectral form. The fitting procedure involved iterative Monte Carlo simulations.

We also quantitatively investigated the possible response of an NM to an ESPE under the single-event hypothesis. The strength of a GLE event can be measured by the integral relative increase I of a sea-level polar NM count rate caused by SEPs above the GCR background [16, 36]. The highest known integral increase of NM count rate, 5300 %*h, was observed during GLE #5. Using the yield function approach [37], we calculated the NM integral increase due to ESPEs, taking into account the GCR background, heavy elements, and solar modulation potential values. We considered three reference events of similar magnitude and estimated the expected NM response for a polar sea-level NM. The estimated integral increase I ranged from ~75000 to ~280000 %*h, which is 15 – 50 times greater than GLE #5. Such a strong count rate enhancement would likely cause saturation of a real NM due to standard dead-time limitations.

4. Conclusion

We developed a new quantitative non-parametric method for reconstructing integral fluences of ESPEs based on scaling the existing GLE spectra to match cosmogenic-isotope data. This approach enabled the consistent reconstruction of integral fluxes for four ESPEs. The method utilizes a Monte Carlo approach to determine the most probable solution and estimate uncertainties. The revised fluence estimates for the 994 CE, 775 CE, and 660 BCE ESPEs are an order of magnitude higher for lower energies (<100 MeV) compared to previous estimates. The results are in agreement with recent reconstructions. These fluence reconstructions are crucial for assessing the potential impact of ESPEs on modern society, as SEPs with energies $E < 100$ MeV pose significant technological and health hazards. The statistical analysis suggests that ESPEs are likely produced by a mechanism similar to regular GLEs, indicating their nature as Black-swan events that can be understood within existing knowledge.

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