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Mind the Gap: New Precise ^{14}C Data Indicate the Nature of Extreme Solar Particle Events

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Key Points:

- A new extreme solar particle event (SPE) was found by Miyake et al. (2021) corresponding to 5410 BCE using precise ^{14}C measurements
- This is the third known "weak" extreme SPE filling a huge observational gap between direct and proxy-based datasets
- This suggests that extreme SPEs likely belong to "normal" solar events and not to an unknown phenomenon, making their detailed study possible

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Abstract

Extreme solar particle events of 775 CE, 994 CE, and 660 BCE are nearly two orders of magnitude stronger than those observed instrumentally. Because of the large observational gap between directly measured and historical events, it was unclear whether they can be produced by the Sun "normally" or from an unknown phenomenon. Recent works by Miyake et al. (2021, doi: https://doi.org/10.1029/2021GL093419) and Brehm et al. (2021, https://doi.org/10.1038/s41561-020-00674-0) start filling the gap with weaker yet extreme events approaching the detectability threshold. More such events are expected to be found in the future but the present result, if confirmed, would imply that the extreme solar events likely represent the high-energy/low-probability tail of the continuous distribution of solar eruptive events rather than a new unknown type of events. However, more statistic is needed for a solid conclusion. This would lead to better understanding of the processes producing such events that is important for their risk assessments for the modern technology.

Plain Language Summary

Hazards related to eruptive solar events such as flares, coronal mass ejections or particle storms are well-known during the recent decades and are studied by the Space Weather research discipline. However, as we know from historical proxy data, solar particle events (SPEs) can be a factor of 100 stronger than the directly observed ones and can potentially cause dramatic damages to modern technologies. With the huge observational gap between directly measured and historical events, it was not clear whether the latter can be produced by the Sun in a "normal" way or from an unknown phenomenon. A recent work by Miyake et al. (2021, https://doi.org/10.1029/2021gl093419) presents a new candidate for the extreme SPE dated to 5410 BCE discovered using high-precision measurements of radiocarbon in tree rings. Together with other recent results by Brehm et al. (2021, https://doi.org/10.1038/s41561-020-00674-0), it starts filling the gap. The result suggests that the extreme solar events likely represent the high-energy/low-probability tail of the continuous distribution of solar eruptive events. This would lead to a better understanding of the processes producing such events that is crucially important for assessments of the related risks for the modern technological society.

1. Introduction

The Sun is known to produce sporadic eruptive events, such as flares and coronal mass ejections (CMEs) when a large amount of energy is released nearly instantly. Such events can cause serious consequences in the Earth's environment, including geomagnetic disturbances, disruptions of radio communications. They can also accelerate charged particles to high energies, producing solar energetic particles (SEPs) that may cause radiation storms at and near-Earth (Desai & Giacalone, 2016; Shea & Smart, 2012; Vainio et al., 2009). The strength of such events may vary as known from instrumental observations during the past decades, including severe storms with hazardous consequences. On the other hand, the era of direct instrumental observation is relatively short, covering several decades, and the experimental data do not allow us to assess the maximum strength of such events nor the probability of their occurrence. The strongest solar particle storm (solar particle event—SPE) directly recorded by ground-based detectors took place on February 23, 1956, while the strongest SPE in the near-Earth space was recorded on August 4, 1972 (Cliver et al., 2014; Usoskin, Koldobskiy, Kovaltsov, Gil, et al., 2020).

The distribution of the integral occurrence probability density function (viz. the probability of an event greater than the given strength to occur) of the directly measured SPE strengths (quantified in the modeled global production of radiocarbon ^{14}C) is shown in Figure 1 as black dots. One can see that the distribution

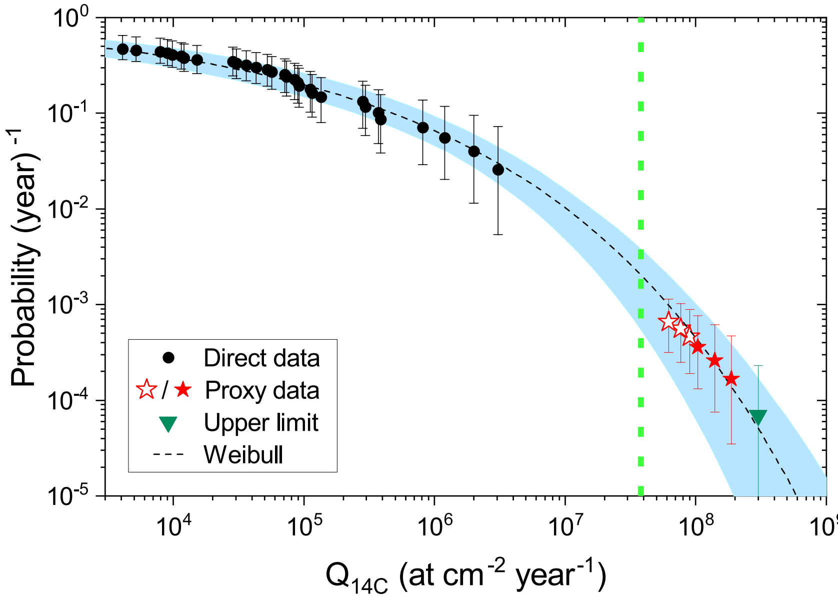

Figure 1. Integral probability density function (IPDF) for the annual production of radiocarbon Q^{14C} due to solar energetic particles (SEPs). The black dots with error bars represent Q_{14C} for the instrumental era SPEs, modeled using the production model by Poluianov et al. (2016) and SEP spectra reconstructed by Koldobskiy et al. (2021). The filled and open red stars denote the confirmed (775 CE, 994 CE, and 660 BCE) and not-yet-confirmed (5410 BCE, 1052 CE, and 1279 CE) extreme SEP events, respectively. The green triangle indicates the upper limit of the SEP events over the Holocene (Miyake et al., 2020). The dashed curve with blue shading depicts the best-fit Weibull distribution $P(>Q) = \exp\left(-\left(Q/11912\right)^{0.226}\right)$. All error bars denote the 95% confidence interval bounds. The green dotted vertical line denotes an approximate detection threshold (Usoskin, Koldobskiy, Kovaltsov, Rozanov, et al., 2020) corresponding to the measurement error of 1.5‰–2‰ in the annual $\Delta^{14}C$ data (Brehm et al., 2021).

is nearly a power law with an index of about −0.4, indicating a weak dependence of the probability of the SPE occurrence on its strength. There is no clear indication of a roll-off of the distribution, and it is not clear whether the distribution can be extrapolated to stronger events that have not been directly observed due to the shortage of the instrumental era (e.g., Gopalswamy, 2018). Its blind extrapolation (e.g., Miroshnichenko & Nymmik, 2014) would suggest that extreme events a factor of hundreds or thousands stronger than those of the instrumental era may appear on the timescale of hundred years. Some constraints on the long-term occurrence of extreme SPE fluxes can be made using cosmogenic data from terrestrial and lunar natural archives (Reedy, 1996; Smart & Shea, 1997, 2002) but they cannot resolve individual events.

Accordingly, the following questions could not be answered based on direct instrumental data:

1. Can stronger events occur?
2. What is the maximum strength of such extreme events the Sun can produce?
3. How often may we expect extreme events on the Sun?
4. What is the mechanism producing extreme events?

2. Present Paradigm of Extreme SPEs

The situation has been changed dramatically in 2012 when an unusual spike was found in ^{14}C in a Japanese Cedar tree as dated to the year 775 CE (Miyake et al., 2012). Different, often exotic origins of the spike were initially speculated, but it was soon shown that this was an extremely strong SPE (Usoskin et al., 2013). This was later confirmed by a multi-proxy analysis (e.g., Mekhaldi et al., 2015). A detailed analysis implied that the event was a factor 40–100 stronger than the strongest instrumental era SPE of February 23, 1956. The extreme event (or a short sequence of events) occurred during the summer of 774 CE (Büntgen et al., 2018; Miyake et al., 2020; Sukhodolov et al., 2017; Uusitalo et al., 2018). A few more similar-type events were

Table 1
Estimated Global Production of ^{14}C, Q_{14C} Due to Strongest Known or Proposed Solar Energetic Particles (SPEs)

Date	Q_{14C} (at cm^{-2})	Status	Reference
775 CE	$1.88 \cdot 10^8$	Confirmed	Büntgen et al. (2018)
660 BCE	$1.4 \cdot 10^8$	Confirmed	O'Hare et al. (2019) and Sakurai et al. (2020)
994 CE	$1.04 \cdot 10^8$	Confirmed	Büntgen et al. (2018)
5410 BCE	$9 \cdot 10^7$	Pending	Miyake et al. (2021)
1279 CE	$7.7 \cdot 10^7$	Pending	Brehm et al. (2021)
1052 CE	$6.2 \cdot 10^7$	Pending	Brehm et al. (2021)
February 23, 1956	$3 \cdot 10^6$	Observed	Usoskin, Koldobskiy, Kovaltsov, Rozanov, et al. (2020)

Note. The status of the events refers to: *confirmed*—a multi-proxy analysis confirms the SPE origin; *pending*—presently, only an increase in Δ^{14}C is known, confirmation in other isotope data is pending; *observed*—calculated for the strongest directly observed SPE.

discovered later, corresponding to the years 993/4 CE (Mekhaldi et al., 2015; Miyake et al., 2013) and 660 BCE (O'Hare et al., 2019; Park et al., 2017), both being slightly weaker than that of 775 CE.

Thus, at present, we know three confirmed extreme SPEs over the past several millennia, all being a factor 30–100 stronger than the ones directly observed during the instrumental era. These confirmed extreme events are listed in the upper block of Table 1 and depicted by the red stars in Figure 1. Although their solar origin is confirmed, it was still unclear whether they represent the high-energy/low-probability tail of the directly observed SPE distribution or a new, previously unknown phenomenon. Producing such events is difficult in the framework of the current models (Gopalswamy, 2018; Miyake et al., 2020).

Also in 2012, super-flares on sun-like stars have been discovered using *Kepler* data (Maehara et al., 2012). These super-flares can be very energetic, several orders of magnitude stronger than directly observed solar flares. However, it is still unclear to what extent these stellar super-flares can be directly applied to the Sun (e.g., Notsu et al., 2019; Reinhold et al., 2020, 2021). It has been proposed that such super-flares are not possible on the Sun because of the lack of magnetic energy (Aulanier et al., 2013).

Although the two types of events, viz. super-flares and extreme SPEs can be interrelated, the statistic was not sufficient to link them theoretically. The gap between the inferred (reconstructed historically or projected from stellar analogs) and directly detected solar events was too large to draw a definite conclusion.

3. Filling the Gap

As proposed basing on theoretical models, the sensitivity of the cosmogenic isotope method is insufficient to detect SPEs of the instrumental era (Mekhaldi et al., 2021; Usoskin et al., 2006), but it allows detecting events a factor of ≈15 stronger than the SPE of February 23, 1956, viz. a factor of 3–7 weaker than that of 775 CE (Usoskin, Koldobskiy, Kovaltsov, Rozanov, et al., 2020). The approximate detection threshold for an SPE in the annual ^{14}C record is shown in Figure 1 as the vertical dashed line. Therefore, if such weaker than 775 CE, yet much stronger than the instrumentally measured events were found, it would helped us studying the occurrence probability distribution of extreme SPEs and identifying their physical background. In particular, it could be distinguished whether the extreme events are formed by the same physical mechanism as the “normal” ones or require some unknown processes to be involved.

Very recently, the unprecedented quality of the cosmogenic isotope measurements made it possible to identify weaker extreme event candidates, to potentially fill the observational gap. Precise annual data of Δ^{14}C for the last millennium (Brehm et al., 2021) had led to the identification of two candidates for historical SPEs in 1052 CE and 1279 CE, that were a factor of 2–2.5 weaker than the strongest SPE of 775 CE and factor 25–30 stronger than that of 1956. In the work by Miyake et al. (2021), another spike in $\Delta^{14}C$ has been identified corresponding to the year 5410 BCE. It was about one half of the 775 CE event and a factor of ≈ 30 as strong as the one of 1956.

Thus, three new SPE candidates (see the central block of Table 1 and white stars in Figure 1) have been found very recently in the annually resolved ^{14}C datasets, approaching the sensitivity threshold of the cosmogenic isotope method (see Figure 1). They are a factor of 2–3 weaker than the extreme event of 775 CE, which remains the strongest solar event over the entire period of the Holocene (Miyake et al., 2020). The statistic of such weaker extreme events is still small, and more similar events are expected to be found—this can be observed in Figure 1 as a visible displacement of the white stars with respect to the best-fit Weibull distribution. However, the very fact of the discovery of the weaker extreme SPEs has a very important implication: the extreme events are likely to be a high-energy/low-probability tail of the "normal" SPEs rather than a special phenomenon. As illustrated in Figure 1, the distribution (integral probability density function, IPDF) of the SPE occurrence can be approximated by a Weibull distribution (Weibull, 1951) with a sharp roll-off, while a simple power law extrapolation of the instrumental era statistic would disagree with the indirect data.

4. Conclusions

After the exciting discovery of the extreme SPEs occurring during the recent Sun's past, it is time to study the phenomenon in detail, in particular, collecting statistic and covering long periods with high-quality data in different cosmogenic isotopes, with a special focus on ^{36}Cl and ^{10}Be measured in polar ice cores. The recent works by Miyake et al. (2021) and Brehm et al. (2021) form the cornerstone for the process of paving a way to detect a larger number of smaller events in the proximity of the sensitivity threshold for the cosmogenic isotope method leading to a breakthrough in our understanding of extreme solar eruptive events and their potential impact on the Earth's environment and our society. In particular, the new result by Miyake et al. (2021) would imply, if independently confirmed, that the extreme SPEs are not manifestations of unknown phenomena but rather high-energy/low-probability tail of the "regular" SPE distribution, making it possible to study them in greater details. Even though many more such events are expected to be found through the past millennia, a tentative conclusion can be drawn already now, thanks to the new level of precision of the radiocarbon measurements.

Data Availability Statement

This work does not contain new original data.

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