Multiradionuclide evidence for an extreme solar proton event around 2,610 B.P. (~660 BC)

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Recently, it has been confirmed that extreme solar proton events can lead to significantly increased atmospheric production rates of cosmogenic radionuclides. Evidence of such events is recorded in annually resolved natural archives, such as tree rings [carbon-14 (14C)] and ice cores [beryllium-10 (10Be), chlorine-36 (36Cl)]. Here, we show evidence for an extreme solar event around 2,610 years B.P. (~660 BC) based on high-resolution 10Be data from two Greenland ice cores. Our conclusions are supported by modeled 14C production rates for the same period. Using existing 36Cl ice core data in conjunction with 10Be, we further show that this solar event was characterized by a very hard energy spectrum. These results indicate that the 2,610-years B.P. event was an order of magnitude stronger than any solar event recorded during the instrumental period and comparable with the solar proton event of AD 774/775, the largest solar event known to date. The results illustrate the importance of multiple ice core radionuclide measurements for the reliable identification of short-term production rate increases and the assessment of their origins.

Significance

This study provides evidence of an enormous solar storm around 2,610 B.P. It is only the third such event reliably documented and is comparable with the strongest event detected at AD 774/775. The event of 2,610 years B.P. stands out because of its particular signature in the radionuclide data [i.e., carbon-14 (14C) data alone does not allow for an unequivocal detection of the event]. It illustrates that present efforts to find such events based solely on 14C data likely lead to an underestimated number of such potentially devastating events for our society. In addition to 14C data, high-resolution records of beryllium-10 and chlorine-36 are crucial for reliable estimates of the occurrence rate and the properties of past solar proton events.

Multiradionuclide evidence for an extreme solar proton event around 2,610 B.P. (~660 BC) could not be used to reliably define the upper limit of our Sun’s eruptive capacity.

Our Sun sometimes produces highly energetic particles, which are accelerated either by magnetic reconnection in solar flares or by shock waves associated with coronal mass ejections. Such energetic particles then follow trajectories along the interplanetary magnetic field lines, which together with the location of the event on the Sun, determine whether these particles hit the Earth’s atmosphere. These phenomena are referred to as solar proton events (SPEs). Such events represent a threat to modern society in terms of communication and navigation systems, space technologies, and commercial aircraft operations (1, 2). Therefore, better understanding the possible magnitudes and occurrence frequency of such events is of great importance for safeguarding space technologies and modern technological infrastructure. During the past ~60 years, these events have been recorded instrumentally and are commonly described quantitatively by their fluence (the number of incident particles per area integrated over the event) of protons with kinetic energy greater than 30 MeV (Fp30). Sometimes, SPEs are so energetic (large fluence >100 MeV; Fp100) that they can lead to increased counts in surface-based neutron monitors known as ground-level enhancements (GLEs). The largest of these GLEs occurred on February 23, 1956 (3) (also called GLE05 according to the numbering of the instrumentally observed GLEs: www.nmdb.eu/nest/gle_list.php) and is estimated to have had an Fp10 of 1.8 × 108 protons per cm2 [Fp10 = 3.0 × 108 protons per cm2 (4)]. The relatively short instrumental record does not allow for robust estimates of the frequency of extreme SPEs, and it cannot be used to reliably define the upper limit of our Sun’s eruptive capacity.

While the use of ice core nitrate to document these events has been rejected (5–7), an extended record of the fluence, frequency, and energy distribution of SPEs can be obtained through the analysis of cosmogenic radionuclides, such as beryllium-10 (10Be), carbon-14 (14C), and chlorine-36 (36Cl) (8–10). These radionuclides are mainly produced via a nuclear cascade triggered by galactic cosmic rays reaching the Earth’s atmosphere on average with much higher kinetic energy than the solar protons. Incoming galactic cosmic rays are modulated by the heliomagnetic and geomagnetic fields, with the strength of this modulation changing from decadal to millennial timescales (11–13). However, strong SPEs can lead to large fluxes of solar protons, causing a short-term rapid increase in the atmospheric production of radionuclides, which are subsequently stored in environmental archives, such as tree rings (14C) and ice cores (10Be and 36Cl). A recent study by Mekhaldi et al. (9) used a series of ice core records (14) to confirm a solar origin for two rapid increases in Δ14C (14C/12C corrected for fractionation and decay relative to a standard) in AD 774/775 and AD 993/994 first identified in tree rings (15–18). Mekhaldi et al. (9) have proposed that the stronger...
of the two events (AD 774/775) had a proton fluence an order of magnitude larger than the strongest instrumentally recorded GLE of February 1956.

Similarly, this study was motivated by the presence of a strong increase in $\Delta^{14}C$ around 2,610 y B.P. (B.P. = years before AD 1950) (19). However, the origin and rapidity of the increase cannot be assessed with the decadal $^{14}C$ data underlying the $^{14}C$ calibration record (IntCal13) during this period. Here, we analyze an extended record of annually resolved $^{14}C$ measurements for this period (19), which displays a strong and rapid $\Delta^{14}C$ increase (Fig. 1). However, the increase in $\Delta^{14}C$ alone does not provide unequivocal evidence for a radionuclide production increase related to a SPE. Therefore, we performed subannual $^{10}Be$ measurements on the North Greenland Ice Core Project (NGRIP) ice core and compared the data with updated and now continuous but lower-resolution Greenland Ice Core Project (GRIP) $^{10}Be$ (~3-y resolution) (20) and $^{36}Cl$ records (21) (~6-y resolution). Following a similar methodology to that of Mekhaldi et al. (9), we use the peak amplitudes and the different energy dependencies of the production rates of the investigated radionuclides to incident energetic particles to investigate if solar modulation of galactic cosmic rays can account for the rapid short-term increase in radionuclide production around 2,610 y B.P. and to estimate the energy spectrum and proton fluence of the SPE. The ice core data largely support the annually resolved $^{14}C$ tree ring measurements, although the inferred $^{14}C$ production rate increase is less abrupt and longer lasting than that for the AD 774/775 event. Based on the combined radionuclide-based evidence, we suggest that a very strong SPE (or a series of strong events) may be responsible for this short-term rapid increase in radionuclide production, an event that was comparable in magnitude to the AD 774/775 event described by Mekhaldi et al. (9) and others (15, 18, 22, 23).

Results

Fig. 1 shows the annual $^{14}C$ tree ring data compared with the smoother IntCal13 calibration record (24), which is represented with a gray envelope. The high-resolution data show a clear peak in atmospheric $^{14}C$ around the 2,610-y B.P. period of about 10$^{10}ee$ over 5 y (19), which is more than twice the typical peak to trough amplitude of roughly 4$^{10}ee$ over a typical 11-y solar cycle (25). This peak in $\Delta^{14}C$ is mostly synchronous with the smaller and smoother $\Delta^{14}C$ increase in the IntCal13 calibration curve during the same time period. However, its shape is different from the $\Delta^{14}C$ increase observed around AD 775 (18), where a 12$^{10}ee$ increase is observed from 1 y to the other. Based on the $^{14}C$ data alone, it is not possible to pinpoint the cause of this $^{14}C$ increase, as it is still in the range exploitable by solar modulation of galactic cosmic rays and its influence on the $^{14}C$ production rate (see below). As the smoothing effect of the carbon cycle makes $^{14}C$ somewhat less suitable to robustly infer rapid production rate changes, we in addition measured $^{10}Be$ in the NGRIP ice core at subannual resolution (about 0.75 y). The data are also complemented by $^{10}Be$ results from the GRIP ice core $^{10}Be$ project (refs. 20 and 26 and this study). The newly measured $^{10}Be$ and GRIP $^{36}Cl$ concentrations are shown in Fig. 2 together with the normalized $^{14}C$ production rate inferred from the annual $^{14}C$ data (more details are in Methods). The relative changes in the $^{10}Be$ data are largely in agreement with the modeled $^{14}C$ production rate considering the large uncertainties in the $^{14}C$ production rate. However, the high-resolution NGRIP and GRIP $^{10}Be$ records indicate a more well-defined $^{10}Be$ production rate peak resembling in shape the $^{10}Be$ enhancement around AD 775 and AD 994 attributed to the effects of extreme solar storms (9). Furthermore, the lower-resolution GRIP $^{36}Cl$ data show a larger relative increase in integrated $^{36}Cl$ excess compared with the integrated GRIP $^{10}Be$ excess around 2,610 B.P. To quantify the production enhancement of each radionuclide, the long-term contribution of galactic cosmic rays on radionuclide production (baseline) was estimated for each record and is plotted as dashed lines in Fig. 2. The NGRIP $^{10}Be$ baseline was calculated from the available data as the average concentration (excluding peak values; ~2,611–2,613 y B.P.). The baseline concentrations for GRIP $^{10}Be$ and $^{36}Cl$ were calculated in the same way (excluding peak values; ~2,610–2,616 y B.P.). However, due to the lower-resolution dataset for the existing GRIP measurements, a period of 50 y was used to estimate the baseline (2,560–2,660 y B.P.) (Dataset S1). The SD of the baseline concentrations was used as uncertainty to estimate the baseline levels. As the $^{14}C$ production rate does not show a well-defined peak, an objective assessment of the peak amplitude is more uncertain. Nevertheless, assuming that the $^{14}C$ peak covers the period from 2,614 to 2,609 y B.P. (Fig. 2A), we deduce an enhancement factor of about four, which is close to the NGRIP $^{10}Be$ estimate if we relate the excess $^{14}C$ production to the baseline $^{14}C$ production from 2,630 to 2,590 y B.P. (excluding the peak period). The resulting baseline concentrations and peak amplitudes for $^{10}Be$ and $^{36}Cl$ are shown in Table 1.

In the case of the high-resolution NGRIP $^{10}Be$ measurements, the relative radionuclide concentration increase occurs over a period of at least 2.3 y (one measurement just before the peak failed to produce a reliable result). However, excess cosmogenic radionuclide production due to SPEs is expected to occur contemporaneously with the initial event unless multiple events occurred over the same ~2-y period. The length of the peak can be attributed to the atmospheric residence time (~1–2 y for $^{10}Be$) (7, 27, 28) or the combination of multiple SPEs and deposition effects. As is the case with $^{10}Be$, we assume that concentration variations of $^{36}Cl$ in ice cores are representative of globally averaged atmospheric production rate changes, which is supported by numerous studies comparing Greenland ice core radionuclide records with tree ring $^{14}C$ and geomagnetic field reconstructions (21, 29, 30). In addition, general circulation climate modeling applied to the $^{10}Be$ transport in the atmosphere and deposition does not support the assumption that $^{10}Be$ concentrations measured in Greenland preferentially represent the polar
production only (31). Furthermore, in the case of solar protons, we expect radionuclide production almost exclusively in the stratosphere due to the comparably lower energies of the solar particles (32). Due to the relatively long lifetime of $^{10}$Be in the stratosphere, the stratosphere can be considered well mixed within each hemisphere (31). The results of Heikkilä et al. (31) indicate that $^{10}$Be variations in Greenland ice cores vary proportionally to the global average $^{10}$Be production rate changes and calculated baseline concentration for $^{10}$Be and $^{36}$Cl (dashed blue line). All ice core data are plotted on the same resolution and number of data points. To obtain the $^{36}$Cl/$^{10}$Be of the enhancement region, we have used two procedures. For the case of $^{10}$Be in NGRIP and $^{36}$Cl in GRIP, we used the procedure of Mekhald et al. (9), which is to subtract the baseline contribution under the peak region using the SD of $^{36}$Cl in GRIP and $^{10}$Be in NGRIP. With this calculation, we get an enhancement of 2.52 ± 0.99. With the same approach for the GRIP data, we would get 1.27 ± 0.36. However, for the case of both isotopes in GRIP, we can take advantage of the fact that variable factors, such as accumulation, solar variability, and duration of the enhancement region, are the same for both isotopes. We calculate the $^{36}$Cl/$^{10}$Be ratio (R) for each of the sample pairs in Fig. 2B. As expected, this ratio outside the peak region is constant within experimental uncertainties ($R = 0.168 ± 0.019$). Thus, when subtracting the baseline contribution of $^{36}$Cl, we can use the $^{36}$Cl baseline estimated from $^{14}$C ($^{36}$Cl baseline = $R \times ^{10}$Be baseline). With this approach, we get that $^{36}$Cl/$^{10}$Be in the enhancement region is equal to 1.27 ± 0.28. The smaller uncertainty compared with using two different core results from the fact that the baseline contributions under the peak regions are not independent. This emphasizes the advantages of having the two isotopes measured in the same core.

The peaks in both $^{10}$Be and $^{36}$Cl concentrations are synchronous with the peak in $^{14}$C production rate after correction for known timescale offsets (29) (SI Appendix). However, the uncertainty in estimating the peak amplitude from $^{14}$C is large, since the enhancement is not well defined in the $^{14}$C record. This global signature increase, which is somewhat reminiscent of AD 774/775 and AD 993/994, strongly points to the occurrence of a strong short-term global increase in radionuclide production rates around 2,610 y B.P.

The three radionuclide records used in this study all display slightly different patterns in terms of the peak duration ranging from 2 to 6 y, despite the expected rapid nature of cosmic ray contribution to the global production and deposition (69 vs. 65%) (Table 2) (“control run” in ref. 31), supporting the assumption that we can expect the relative changes in radionuclide deposition in Greenland to be close to the relative changes in global average production. Radionuclide concentration/production values exceeding 3σ of the calculated natural background level around 2,610 y B.P. are assumed to be related to the event and have been integrated into a single year (with calculated baseline). These integrated values are represented as enhancement values (Table 1) and include errors incorporating uncertainties in measurement as well as a baseline variability, which results from the 11-y solar modulation variability and noise inherent in the data. The NGRIP $^{10}$Be measurements indicate a concentration peak factor (enhancement divided by baseline estimate) of 2.52 ± 0.91, and the GRIP $^{10}$Be and $^{36}$Cl data indicate concentration peak factors of 4.99 ± 0.99 and 6.36 ± 1.36, respectively. The GRIP $^{10}$Be numbers were calculated the same way as for the corresponding $^{36}$Cl data (same resolution and number of data points). To obtain the $^{36}$Cl/$^{10}$Be of the enhancement region, we have used two procedures. For the case of $^{10}$Be in NGRIP and $^{36}$Cl in GRIP, we used the procedure of Mekhald et al. (9), which is to subtract the baseline contribution under the peak region using the SD of $^{36}$Cl in GRIP and $^{10}$Be in NGRIP. With this calculation, we get an enhancement of 2.52 ± 0.99. With the same approach for the GRIP data, we would get 1.27 ± 0.36. However, for the case of both isotopes in GRIP, we can take advantage of the fact that variable factors, such as accumulation, solar variability, and duration of the enhancement region, are the same for both isotopes. We calculate the $^{36}$Cl/$^{10}$Be ratio (R) for each of the sample pairs in Fig. 2B. As expected, this ratio outside the peak region is constant within experimental uncertainties ($R = 0.168 ± 0.019$). Thus, when subtracting the baseline contribution of $^{36}$Cl, we can use the $^{36}$Cl baseline estimated from $^{14}$C ($^{36}$Cl baseline = $R \times ^{10}$Be baseline).

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| Table 1. Summary of results for the 2,610-y B.P. event |
|---------------------------------|-----------------|-----------------|-----------------|
| Variable                        | NGRIP $^{10}$Be | GRIP $^{10}$Be  | GRIP $^{36}$Cl  |
|---------------------------------|-----------------|-----------------|-----------------|
| Baseline, atoms per gram        | 1.60 ± 0.50 x 10^4 | 1.23 ± 0.13 x 10^4 | 2.08 ± 0.3 x 10^3 |
| Integrated enhancement, atoms per gram | 4.03 ± 0.76 x 10^4 | 6.16 ± 0.95 x 10^4 | 13.2 ± 2.4 x 10^3 |
| Peak factor                     | 2.52 ± 0.91  | 4.99 ± 0.93  | 6.36 ± 1.36  |
| $^{36}$Cl/$^{10}$Be             | 2.52 ± 0.99  | 1.27 ± 0.28  |

Estimates of the baseline production, enhancement (integrated peak concentration above baseline), and enhancement factor for $^{10}$Be and $^{36}$Cl (atoms per gram ice) for the 2,610-y B.P. event as shown in Fig. 2. The peak factor relates the integrated radionuclide enhancement to the baseline radionuclide production over a year. Uncertainties are based on error propagation, including measurement errors and baseline variability of 1σ. The peak factor for the NGRIP $^{10}$Be data contains an additional uncertainty, since one $^{10}$Be measurement just before the $^{10}$Be increase was lost. Furthermore, the baseline calculation for NGRIP might be less robust due to the relatively short dataset. The error calculation for GRIP $^{36}$Cl/$^{10}$Be is explained in the text. The $^{36}$Cl/$^{10}$Be ratio for NGRIP $^{10}$Be is based on $^{10}$Be from NGRIP and $^{36}$Cl from GRIP.
A feature of cosmogenic radionuclides by solar energetic protons (4), this pattern is in accordance with the expected production signature of galactic cosmic ray flux reaching the Earth. Within the relatively large errors, the $^{14}$C data alone cannot be used to pinpoint the source of the radionuclide enhancement. A reason could be the relatively low sensitivity of the atmospheric $^{14}$C to short-term enhancements in the $^{14}$C production rate and the corresponding large errors in the reconstructed $^{14}$C production rate. In the case of GRIP $^{10}$Be and $^{36}$Cl, the broad ~6-y peak can be attributed to the low resolution of the dataset owing to sample size requirements of the original GRIP project. The $^{36}$Cl enhancement reported here is comparable with $^{36}$Cl peaks around AD 774/775 and AD 993/994 (9). The estimates for the relative $^{10}$Be and $^{36}$Cl increases are listed in Table 1. The production of $^{36}$Cl was more enhanced during the 2,610-y B.P. event compared with $^{10}$Be. This pattern is in accordance with the expected production signature of cosmic ray radionuclides by solar energetic protons (4, 35). As shown in Fig. 2, the short-term rapid increase in $^{10}$Be cannot be explained by typical solar modulation. More specifically, the red band in Fig. 24 represents the $^{10}$Be production range attributable to a solar modulation $\Phi$ varying between 500 and 1,200 MeV, which is the range of variance estimated for the past 60 y (36). Fig. 24 shows that the three data points assumed here to be related to the same event are all above this production range. Modeled $^{14}$C production for the 2,610-y B.P. period supports the increased production rate, although the peak in modeled $^{14}$C production has large uncertainties and appears broader than expected as discussed above.

**Discussion**

Excluding Other Sources/Support for a Solar Origin. The Sun impacts the radionuclide production rate indirectly by modulating the galactic cosmic ray flux reaching the Earth’s atmosphere, most notably in the form of the 11-y solar cycle (37). The 2,610-y B.P. production increases in $^{14}$C, $^{10}$Be, and $^{36}$Cl described in this study cannot be explained by this modulation for several reasons. First, there is a theoretical limit for the production increase that is reached when solar shielding of galactic cosmic rays shifts from above average shielding (which corresponds to the estimated baseline) to no shielding as mentioned above. The red and blue bands in Fig. 2 show the typical variability in radionuclide production rates over an 11-y solar cycle based on the past 60 y. If we assume that the 2610-y period is interrupted by a period of completely absent solar shielding, we would expect an ~65% increase in the radionuclide production rate exceeding the upper limit of this range (red and blue bands in Fig. 2) (36). Both the high-resolution GRIP $^{10}$Be and GRIP $^{36}$Cl concentration increase exceed this theoretical threshold, while the GRIP $^{10}$Be data are at that limit within uncertainty. Furthermore, the lower resolution of the GRIP data and the smoothing during transport and deposition of $^{10}$Be and $^{36}$Cl lead to a reduced amplitude in the radionuclide data compared with the actual production rate increase. Second, the effect of solar modulation on the production of $^{10}$Be and $^{36}$Cl is very similar (i.e., leading to changes of the $^{10}$Be/$^{36}$Cl ratios even during varying solar or geomagnetic shielding of galactic cosmic rays of less than 1%) (38). The larger enhancement of $^{36}$Cl compared with $^{10}$Be for the 2,610-y B.P. event, therefore, points to another process, likely a production rate increase due to lower-energy solar particles, as the ratio is expected to increase if solar protons significantly contribute to the radionuclide production rate (4).

The incorporation of $^{14}$C into the carbon cycle results in an attenuation of high-frequency peaks in the atmospheric $^{14}$C concentrations. This leads to larger errors of the reconstructed $^{14}$C production rate changes and therefore, at least in this case, to difficulties in robustly identifying the SPE event even with precisely measured $^{14}$C data (Fig. 24). Due to the relatively large errors of the inferred $^{14}$C production rate, a solar modulation origin of the $^{14}$C peak cannot be excluded. However, the $^{14}$C peak around 2,610 y B.P. (Fig. 1) exceeds significantly the $^{14}$C variations during an 11-y cycle, which are typically in the range of 4‰ (25). The differences to $^{10}$Be could be attributed to $^{14}$C measurement uncertainties, which result in the large error band of the reconstructed $^{14}$C production rate, cycle rate uncertainties, and/or transport effects on $^{10}$Be. Furthermore, the $^{10}$Be and $^{14}$C production rate differences around the 2,610-y B.P. peak are similar to the $^{10}$Be–$^{14}$C differences before and after the peak (Fig. 24), indicating the challenges of robustly identifying short-term production rate increases with individual radionuclide records.

Aside from solar modulation and the occurrence of extreme solar events, several theories have been proposed as responsible for rapid short-term increases in cosmogetic radionuclide production. One such theory involves a short gamma ray burst resulting in irradiation of the atmosphere by a flux of high-energy gamma rays (18, 39, 40). Based on production cross-section measurements, Raisbeck et al. (41) estimated an about four times larger relative $^{14}$C production based on annual $^{14}$C tree ring measurements adds support to our hypothesis but also, leaves open questions regarding $^{14}$C measurements alone to robustly infer past solar storm events.

**Spectral Hardness.** For a SPE to result in a measurable increase in cosmogetic radionuclide production, its proton fluence is expected to be large (4). This is illustrated by the fact that no SPE in the instrumental period has been unequivocally linked to
10Be concentration enhancements in ice cores (42–44). The AD 774/775 and AD 993/994 radionuclide enhancements (9) were the first to be conclusively linked to major solar events. For the purpose of adding to this previous work and constraining the probability for and possible magnitude of such events, it is important to further characterize the 2,610-y B.P. event. One crucial parameter is the spectral hardness of the event, which is a measure of the energy distribution of the protons for a given event. Additionally, we can provide an estimate of the event’s proton fluence, which can then be used for comparison with modern day events. Considering the different energy dependencies of the production yield functions of cosmogenic radionuclides (4, 45), the inferred radionuclide production rate increases can be linked to the spectral hardness of a SPE. Key to this estimation is the phenomena whereby the yield functions of 10Be and 36Cl have very different shapes at low energies, with 36Cl production being relatively more sensitive to incident protons around 30 MeV, whereas 10Be (compared with 36Cl) is more sensitive to protons with energies above 100 MeV (4). Webber et al. (4) computed the impact of a series of historic SPEs on atmospheric production of 10Be and 36Cl. That relationship was expressed using an enhancement factor ratio 36Cl/10Be, with high energy spectra events resulting in ratios typically between one and three and softer energy spectra events resulting in ratios typically larger than four. Similarly, as Mekhaldi et al. (9) estimated the hardness of the AD 774/775 and AD 993/994 events, we will relate our observed 10Be/36Cl production increase ratio to calculated ratios for known events (4) to assess the spectral hardness of the 2,610-y B.P. event. Estimating the peak height in relation to the baseline includes considerable uncertainties, and the ratios GRIP 10Be vs. GRIP 36Cl and NGRIP 10Be vs. GRIP 36Cl differ and illustrate these uncertainties. The ratio based on the GRIP 10Be and 36Cl data is likely more robust, as the measurements come from the same ice core; therefore, the time periods of the integrated radionuclide enhancements are identical. To include the above-described uncertainties, we calculated the error-weighted means of the 36Cl/10Be ratios (2.52 ± 0.99 and 1.27 ± 0.28, respectively) and obtain an error-weighted mean value of 1.4 ± 0.3 for the 2,610-y B.P. radionuclide enhancement. This places the 2,610-y B.P. event in the high spectrum category—likely even harder compared with that for the AD 774/775 event. In addition, when comparing this ratio with instrumentally recorded historic events (4, 9), we find that the best modern analog with a similar hard spectrum is that of January 2005 (SPE05 or GLE69). The envelope ranges from the lowest X05 scaling factor of 67 to the highest X05 scaling factor (based on NGRIP 10Be only) of 143. Therefore, even when the lowest-bound error estimate is considered, the F30 for the 2,610-y B.P. event exceeds 1010 protons per 1 cm². Similar to the even more extreme AD 774/775 event, a SPE of such magnitude occurring in modern times could result in severe disruption of satellite-based technologies, high-frequency radio communication, and space-based navigation systems (1).

In conclusion, two 10Be records from this study indicate a rapid enhancement in radionuclide production around 2,610 y B.P. (~660 BC), which is synchronous with a large concentration enhancement in the GRIP 36Cl record. Numerous 10Be data are, considering the uncertainties, largely in agreement with the ice core-based increases, although 14C does not provide an as unequivocal signal as for the AD 774/775 and AD 993/994 events. We have shown that these concentration enhancements cannot be explained by decreased solar modulation. In addition, the different enhancement factors represent the typical isotopic fingerprint of a SPE (4, 9). Considering these large radionuclide enhancements, we suggest the identification of another extreme SPE, which was most likely characterized by a very hard spectrum and an estimated F30 of 2.09 (±0.75) × 1010 protons per 1 cm² [F100 = 6.3 (±2.28) × 109 protons per 1 cm²]. Hence, the 2,610-y B.P. SPE was an order of magnitude more energetic than the largest GLE of February 1956 (GLE05) and similar in magnitude to the remarkably strong and hard AD 774/775 ancient SPE.

Methods

14C Production Rate. In addition to 10Be and 36Cl, we utilized annually resolved tree ring δ14C measurements (19) to calculate 14C production rates for the 2,610-y B.P. period. Radiocarbon measurements from geological archives are not a direct reflection of atmospheric 14C production but rather, a damped and time-shifted signal of it due to changes of reservoir sizes and exchange fluxes in the global carbon system (46, 47). We, therefore,
calculate the $^{14}$C production rates to correct for postproduction effects as a result of $^{10}$Be entering the carbon cycle (SI Appendix).

$^{36}$Cl Data. Before this study, there were no published high-resolution $^{36}$Cl data for the 2,610±y B.P. period. Completing the $^{36}$Cl record with a resolution of about 3 y supports the exceptional $^{36}$Cl increase around 2,610 B.P. The NGRIP ice was sampled at a constant resolution of ~11 cm, which resulted in an average temporal resolution of about 0.75 y. That is with the exception of two samples, which were sampled at a resolution of 18.3 cm (1.2-y resolution) due to less ice available, which would hinder quality measurements (SI Appendix).

$^{36}$Cl Data. Existing $^{36}$Cl measurements in the GRIP ice core (21), which have an average resolution of ~6–7 y, were investigated for the same period. Due to the greater sensitivity of the $^{36}$Cl production rate for lower-energy solar protons (4), $^{36}$Cl is, therefore, of particular interest when investigating SPEs.

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