Isotopic terrestrial imprints of solar superflares

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Abstract. The extreme cosmic event that occurred in AD 775 was detected using 14C measurements in tree rings and 10Be, 36Cl abundances in polar ice cores. Perhaps it is the most powerful solar proton event in the past several thousands of years. Simulation of isotope production with the spectra of solar flares observed in the modern era (23.02.56, 04.08.72 etc.) showed that to produce the measured amount of radionuclides, the particle fluence in the AD 775 event has to be by tens - hundreds times greater than the modern powerful solar events. The results of calculations of long-lived cosmogenic radionuclides (14C, 10Be, 36Cl) production in the Earth's atmosphere are presented.

1. Introduction
Production of cosmogenic radionuclides in the Earth’s atmosphere is caused by nuclear reactions of cosmic rays (CRs). The concentration of long-lived 14C, 10Be and 36Cl isotopes in natural archives has reflected the history of atmospheric irradiation. Their records demonstrate temporal variability which can be partly attributed to the known astrophysical phenomena [1]. For example, correlations of the nuclide concentration records with long-term CR intensity variations due to the changes in solar activity and geomagnetic field were comprehensively studied [2]. However, another class of extraterrestrial sources – the impulsive sporadic events such as powerful solar proton events (SPEs) and gamma-ray bursts (GRBs), could momentarily increase the production rate by several orders of magnitude. Therefore, they could produce a sharp rise of the atmospheric concentration of the nuclides. Such an enigmatic sharp increase of the 14C relative concentration (δ14C) in tree rings dated AD 775 was discovered by Miyake et al. [3]. It was later confirmed by other groups in different tree ring collections [4, 5, 6] and in corals [7]. Data analysis from both hemispheres confirms duration of the initial event which was probably shorter than one year [6]. These results stimulated intensive discussion on a possible origin of the unexpected phenomenon. Several working hypothesis even such exotic as a comet impact on the Sun and Earth [7] have been proposed since. At present, only two of them have survived as realistic. They are a solar superflare with very hard energy spectrum of protons [4] and GRB of Galactic origin [8, 9]. For SPE hypothesis the isotope production mainly depends on the particle superflare spectra and (in a minor degree) on the geomagnetic field strength at that period.

In this paper we model production of 14C, 10Be and 36Cl by SPEs with different spectra. We demonstrate also that these spectra result in the significant difference of the isotopic imprints (we mean both global production rate, Q, and the local one in the polar troposphere, Q1). Additionally, we
study the influence of the geomagnetic field variations because of significant screening effect for low-energy particles penetrating the Earth’s atmosphere.

2. Method
We used the standard GEANT4 toolkit which is based on the Monte Carlo method for simulations of atmospheric interactions of high-energy charged particles. The GEANT4 includes several intranuclear cascade models (BIC and BERT) and cross section data in a wide energy range, which are continuously updated. As was shown in our previous paper[10] the BERT model results agree better with previous simulations of the $^{10}$Be atmospheric production by GCRs, and the BIC model better fits actual estimates of $^{14}$C global production rate. Production rates were calculated for 0-130 km altitudes with 1 km step with particle flux penetrating the Earth’s atmosphere being isotropic. These yield functions were further convoluted with the SPE spectra taking into account geomagnetic rigidity cutoff.

![Fig. 1](image_url) Spectra of SPEs used for calculations.

3. Isotopic imprints of powerful SPEs
Under the term “isotopic imprint” of a certain event we shall understand the resulted peculiarity of isotopic composition fixed in terrestrial natural archives. To model possible imprints, caused by SPEs, it is necessary to assign the flux and energy spectra of protons. Direct measurements of solar accelerated particles started in the 50’s of the last century. Early observations were carried out with neutron monitors located on the ground and thus sensitive to the high-energy part of the spectra of penetrating atmosphere particles. Later on the low-energy part of solar particles was studied by the instruments deployed in outer space.

Atmospheric production rate of a nuclide is a function of the incident particle energy. It is known that for individual SPEs of a given total energy, injected into the atmosphere, the solar proton flux and energy spectra may differ significantly. Therefore, we present calculations of the nuclide production for a number of observed powerful flares with the hardest (23.Feb.1956) and the softest (04.Aug.1972) energy spectra (see, e.g., [11], [12], [13]) and also for three theoretical ultimate spectra (Fig. 1).

According to our simulations the required SPE fluence for the considered flares has to be higher by factors ($\alpha$) presented in Table 1 in order to fit $^{14}$C spike. Ratio of the global productions $Q(^{14}$C)/$Q(^{10}$Be) for the considered events is almost constant, and $Q(^{10}$Be)/$Q(^{36}$Cl) ratio rises by 1-14 times with the growth of the characteristic rigidity (or mean particle energy) of the event (Table 1).
Table 1. Modeled global production Q. Here α is the factor by which SPE fluence should be multiplied to account for the AD 775 $^{14}$C excess signal.

| SPE spectrum | 1956 | 1972 | mean | soft | hard | [14] |
|-------------|------|------|------|------|------|------|
| α           | 89   | 334  | 1.4  | 176  | 0.087|      |
| $^{10}$Be, $10^6$ at/cm$^2$ | 4.9  | 3.5  | 4.8  | 4.4  | 4.8  | 0.9  |
| $^{36}$Cl, $10^6$ at/cm$^2$ | 0.46 | 3.4  | 0.79 | 2.4  | 0.34 | 0.3  |
| $^{14}$C/$^{10}$Be | 41   | 57   | 42   | 46   | 42   | 233  |
| $^{10}$Be/$^{36}$Cl | 11   | 1.0  | 6.0  | 1.8  | 14   | 2.9  |
| $^{10}$Be excess | 18   | 13   | 18   | 16   | 18   | 3.4  |
| $^{36}$Cl excess | 10   | 76   | 18   | 53   | 7.6  | 6.3  |
| $^{10}$Be/GCR | 5.9  | 4.2  | 5.8  | 5.3  | 5.8  |      |
| $^{36}$Cl/GCR | 10   | 75   | 17   | 52   | 7.5  |      |

As was shown in [10] the tropospheric $^{10}$Be production by GCRs provides the observed deposition rate at central stations of Greenland and Antarctica (at the mean tropopause height 9-10 km). Also, it provides deposition variations during the 11-yr solar cycle without significant contribution of the stratospheric $^{10}$Be. One can see from Fig. 2 that its production in polar troposphere at mean tropopause height 9-10 km can account for the additional instant deposition of $^{10}$Be for the AD 775 event assuming its spectrum close to that of the 1956 flare (or even harder). For the events similar to the 1972 flare the explanation is possible only under assumption of main contribution of the stratospheric $^{10}$Be. Analogous inference for $^{36}$Cl is impossible because even maximal tropopause height (12 km) does not result in the observed deposition rate for AD 775 at any particle spectra. The deposition rate pulse of $^{36}$Cl in Central Greenland could be accounted for only at prevailing contribution of the stratospheric $^{36}$Cl produced by superflare. Similar result was obtained for the GCR modeling [10].

Fig. 2. Tropospheric production rate $Q_T(^{10}$Be) (in experimental deposition rate units, see [14]) for different tropopause heights. Grey bar is the AD 775 $^{10}$Be excess with errors based on data from [14].
4. Conclusions
The main results of the present paper are as follows:

1. To account for the AD 775 event by solar superflare the particle fluence has to be by 89 times larger than that of the 23.Feb.1956 event (hard spectrum) and 334 for the 04.Aug.1972 event (soft spectrum).

2. The Q(\(^{14}\)C)/Q(\(^{10}\)Be) production ratio for SPE turns out to be 40-60 weakly dependent on the incident particle spectra and geomagnetic field if 0<M(t)/M<1.3. At the same time the Q(\(^{10}\)Be)/Q(\(^{36}\)Cl) ratio lies within the range 1-14 mainly depending on the SEP energy distribution.

3. The global production of \(^{36}\)Cl for all simulated event spectra exceeds its deposition rate by 1.2-12 times for the AD 775 event.

4. The tropopause height and its variations after the event (AD 775) may significantly affect the amplitude of the signal in \(^{10}\)Be. To explain the observed deposition rate for the AD 775 event the troposphere height must be in the range of 8.5-10.5 km.

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