Isotopic imprint of the Solar system encounter with interstellar gas cloud around 660 BC (2610 BP)

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Abstract. We analyse the long lived radio nuclide data (14C, 10Be and 36Cl) in tree rings and Greenland ice cores referred to the 660 BC event. The hypotheses of solar superflare impact on the atmosphere and Solar system collision with small sized dense interstellar cloud are considered. Decisive role in clarifying the situation is the experimental data on other isotope content available in ice for the periods under discussion. The data on 10Be and 36Cl (GRIP and NGRIP stations in Greenland) during the 660 BC event favour the second hypothesis. Various assumptions on the relationship between isotope production and deposition rates in the atmosphere are considered.

1. Introduction

Radiocarbon content variations in the terrestrial atmosphere (or in tree rings) may be caused by several reasons. Among the most significant one may usually consider Galactic gamma-ray bursts, global geomagnetic field, solar energetic particle (SEP) events, modulation of the Galactic cosmic rays (GCRs) by solar activity and possibly climate changes. All those are manifested in the isotope data with different amplitudes and time behavior including their different production ratios and, hence, deposition ratios likely modified by their transport in the atmosphere. Here we have utilized two approaches for the deposition rate models, namely, 1) proportionality of local tropospheric production and deposition rates and 2) transport model of Heikkilä et al. [1] which describes 10Be deposition rate at a certain geographic point as a sum of its production at other regions within the atmosphere (see below).

Recent experiments carried out by Miyake et al. [2] have discovered several prompt increases in the radiocarbon content (\(\Delta^{14}\text{C}\)) in tree rings. Here we discuss the 660 BC event enhancement in detail. Recently, we have published the hypothesis about Solar system "collision" with interstellar small-sized cloud [3] as a possible reason for the radiocarbon event around 5480 BC with anomalously rapid \(^{14}\text{C}\) concentration increase in tree rings. Wavelet analysis of these data has shown the presence of the 11-year periodicity attributable to the "normal" solar activity. The 660 BC radiocarbon event is more difficult to analyze because of scarce experimental points. However, we also relied on the assumption of the Solar system transaction of the interstellar gas cloud. In contrast, the authors [4, 5] prescribe this
kind of events to the abnormal solar activity influence and/or successive solar superflare(s) impact on
the Earth’s atmosphere. One should note that quite prolonged time increase (~5-6 years) in the 660 BC
event requires bunch of subsequent powerful superflares resulting in the observed ascending part of
the $\Delta^{14}$C($t$). Single superflare (or gamma-ray burst) must result in a very short rise time of the $\Delta$
$^{14}$C($t$) value lasting ~1-2 years.

In the present paper we also involve and analyze the recently obtained $^{10}$Be and $^{36}$Cl data [5] in
order to check solar superflare hypothesis for the $\Delta^{14}$C($t$) pulse formation in the atmosphere and
compare with our hypothesis.

2. Production ratios of the isotopes

In order to simulate the radiocarbon ($^{10}$Be and $^{36}$Cl as well) production rates in the atmosphere one
should use the yield-function approach presented in our previous papers [6, 7]. Dependence of this
yield-function on the atmospheric altitude allows one to simulate not only the global isotope
production rate but also its tropospheric and stratospheric parts separately (denoting them as $Q_T$ and
$Q_S$, correspondingly). Also, we have taken into account both protons and alpha-particles incident on
the top of the atmosphere. Their energy spectra were assumed to be the same (corrected by the
abundance factor ~10 %) and close to the spectra of 1956 flare if we suppose flare originated
enhancements in the atmospheric radiocarbon (and other isotopes) concentrations. For the energy
spectra of GCRs in the vicinity of heliosphere (LIS), providing maximal values of the isotope
production rates, we have accepted some modeling forms available in literature [3].

To compare isotope imprints measured in ice cores with our simulations it is necessary to accept
some model of snow formation and atmospheric transport model as well. A simplest assumption for
the latter (mainly for $^{10}$Be) is the proportionality between tropospheric production $Q_T$ and deposition
rates. It was already used in the paper by Frolov et al. [8] which result in the necessity of the
tropospheric height to be around ~9-11 km. This assumption means very close location of the $^{10}$Be
production to its deposition site. At the same time there are some models which describe the transport
of $^{10}$Be in a rather complicated manner [1]. According to the model of Heikkilä et al. [1] the deposition
of $^{10}$Be, for example, at NGRIP station (75.1N; 42.32W), $D$($60^\circ$-90$^\circ$ N) in at/cm$^2$s, is determined by its
transport from another geographic regions (see Table 3 of that paper). Namely,

$$D(60^\circ$-90$^\circ$ N)= 0.19Q_T(60^\circ$-90$^\circ$ N)+0.05Q_T(30^\circ$-60$^\circ$ N)+0.02Q_S ,

where $Q_T$ (at/cm$^2$s) is the tropospheric production rate of the isotope integrated over altitude at
corresponding latitude interval marked in parenthesis, and $Q_S$ is its stratospheric part integrated over
altitude and averaged over latitude in spherical geometry. Though originally the $Q_S$ value does depend
on latitude it rapidly becomes homogeneous due to fast mixing in the stratosphere as was shown in
paper [1].

The comparison of both approaches ([1] versus [8]) are presented below in Table 1. Simulating the
value of $D$ in the framework of the model [1] we have used dependence of the isotope production rates
on altitude and latitude which implied some model for the terrestrial magnetic moment $M(t)$ and its
past variations during the periods under discussion. For the 660 BC event it was by ~50 % higher than
its contemporary value ($M_0=7.72*10^{25}$ G cm$^3$ for the 2015 epoch with the geomagnetic pole locating at
80.4N; 72.6W), and for the 5480 BC event one may consider its changes relative to this value
insignificant [10]. In addition, it is assumed to have dipole structure with the cutoff rigidity $P(\lambda)$ at
latitude $\lambda$ in the form of $P(\lambda)=14.9(M/M_0)\cos^3\lambda$ (GV). Another important issue may be location of
the magnetic pole in the past with respect to the GRIP and NGRIP stations because its migration
influences the local isotope production rate via cutoff rigidity (cutoff energy) changes. It is known that
magnetic pole drifts permanently within ~15° by latitude during the last 7000 years [11]. However, the
use of Heikkilä et al.’s model presented in their Table 3 [1] implies the averaging over 30° therefore
we omit this effect from our consideration. Our theoretical results are summarized in Table 1 along
with the experimental records from GRIP (72.34N; 37.34W) and NGRIP (75.1N; 42.32W) [5].
Table 1. Comparison of different models for the $^{10}$Be and $^{36}$Cl deposition ratios in ice using their transport in the atmosphere [1, 8] with the experimental data [5].

|                | $^{14}$C glob | $^{36}$Cl glob | $^{10}$Be [1] | $^{10}$Be/$^{36}$Cl | $^{10}$Be [8] | $^{10}$Be/$^{36}$Cl |
|----------------|---------------|----------------|---------------|---------------------|---------------|---------------------|
| LIS            | at / cm$^2$/s | at / cm$^2$/s  | at / cm$^2$/s | at / cm$^2$/s       | at / cm$^2$/s | at / cm$^2$/s       |
| Langner [13]   | 2.84E+00      | 3.46E-03       | 2.07E-02      | 6.0                 | 1.72E-02      | 5.0                 |
| Orlando [12]   | 2.60E+00      | 3.13E-03       | 1.87E-02      | 6.0                 | 1.59E-02      | 5.1                 |
| 660 BC Event data [5] | 2.70E+00 | 3.00E-03       | 1.70E-02      | 5.7                 | 1.70E-02      | 5.7                 |
| Superflares 1956 | 1.55E+08 | 4.13E+05       | 1.16E+06      | 2.8                 | 5.14E+05      | 1.2                 |

It is clearly seen that superflare conception really contradicts actual isotopic imprint ratios obtained in the experiments (GRIP). Here we really use only GRIP data because it is not fully correct to determine isotopic ratios extracted from different ice cores of different geographic locations.

3. Treatment of the data

When calculating the radiocarbon production rate in the atmosphere, $Q(t)$, we use 5-reservoir model of radiocarbon cycle. This approach was applied earlier and described elsewhere [3, 7, 9]. Results are shown on Figure 1. Here we also invoke $^{10}$Be data to study 660 BC event in more detail [5]. Present calculations are based on the experimental data points measured in $^{10}$Be atoms per gram of ice. One should convert them into deposition rate (atoms/cm$^2$/year) using the ice accumulation rate at a certain location. They are ~23 g/cm$^2$/year and ~14.7 g/cm$^2$/year for the GRIP and NGRIP, respectively (ice density $\rho \sim 0.8$ g/cm$^3$). To reconstruct local production rate in the atmosphere one needs some factor $\xi$ establishing proportionality between $^{10}$Be global production rate and its local deposition rate. This magnitude was estimated to be $\xi = 3.23 \pm 0.41$ for the period 1951-1994 for the NGRIP station [14]. Evidently, here we follow our simplest assumption [8] trying to explain $^{10}$Be data (see Section 2).

![Figure 1. Radiocarbon production rate in the atmosphere around 660 BC [15].](image)

First of all we try to analyze $^{10}$Be records presented in [5] for GRIP. Strong increase of $^{10}$Be concentration around 2610 BP (Figure 2A) hampers statistical analysis of the spectral content of beryllium variations during 2561-2660 AD. In order to attenuate influence of this peak-type "sub-
event" we removed 10-year average from the initial $^{10}$Be records (Figure 2B). This high-frequency part (HFP) of the series was analyzed by means of both wavelet and Fourier approaches. It is seen from the local wavelet spectrum (Figure 2C) that a chain of six individual cycles with the periods 9.5-12.5 years is present in the rest HFP during 2564-2627 BP. There are also details with comparable scales (8.0, 15.0 yrs). As a result a significant peak at 10.8 year appears in Fourier spectrum (Figure 2D).

Figure 2. A – Concentration of $^{10}$Be in polar ice [5] around 660 BC (660 BC+1950 AD=2610 BP) at GRIP station. Thick line is 10-years average; B – $^{10}$Be records after subtracting the 10-year averaged trend – the rest high-frequency part (HFP); C – local wavelet spectrum (the MHAT basis) of the HFP; red arrows denote the corresponding period intervals referred to the peaks; D – Fourier spectrum of the
HFP (SPD – spectral power density). Dotted line is the 0.99 confidence level (c.l.) calculated for the red noise with the autocorrelation coefficient AR(1)=0.76.

![Figure 3](image_url)

**Figure 3.** Modulation potential $\phi$ (GV) for the 660 BC event at different proportionality coefficients between local $^{10}$Be deposition at NGRIP (A), GRIP (B) stations and production rates (parameter $\xi$, see text).

In order to make some inferences on theoretical reasons of the period under discussion we carried out additional calculations of the modulation potential during this time interval for the most acceptable local spectra of the Galactic cosmic rays in the vicinity of heliosphere [12, 13]. It is possible to do so on the basis of radiocarbon and $^{10}$Be data independently though some details are different. Namely, the radiocarbon is distributed homogeneously in the atmosphere therefore the measurements in tree rings are mainly determined by its global production rate while $^{10}$Be deposition in ice is far from homogeneous. As a result, only time variations in the radiocarbon concentrations are important, and for $^{10}$Be its spatial variations must be taken into account. Thus, the modulation potential reconstructions, made according to the approach by Kovaltsov et al. [16] from $^{14}$C and $^{10}$Be data, are shown on Figure 3.
4. Discussion and conclusion

New experimental data on $^{10}$Be and $^{36}$Cl in Greenland allows one to reject solar superflare hypothesis because this conception has two significant objections. First, the rise time of the considered event (660 BC) is significantly longer (5-6 years) than that originated from pulse injection in the atmosphere. Second, the isotopic $^{10}$Be/$^{36}$Cl ratio at GRIP ice core by 2-5 times higher than that simulated for the SEP event(s) (analog of the 1956 flare). So, this approach requires a series (about 100) of super powerful flares more or less homogeneously distributed within 5-6 years. Such a situation never observed in instrumental era. Additionally, the presence of the ordinary 11-yr periodicity around the 660 BC event shows the normal state of solar activity within the considered period.

On the other hand, the 660 BC event can be accounted for the Solar system encounter with the small-sized (R~60 AU) high-density (n~100 cm$^{-3}$) interstellar cloud. In this case the isotopic imprint well agrees with the $^{14}$C spike magnitude, its time behaviour and the isotopic ratio ($^{10}$Be/$^{36}$Cl) measured at GRIP ice core in Greenland (see Table 1).

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