Heliospheric modulation potential reconstructed by means of the radiocarbon data from the beginning of 11th century AD till the middle of the 19th century AD

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Abstract. This paper presents the results of reconstruction of the heliospheric modulation potential based on the content of ¹⁴C cosmogenic isotope in natural archives from the beginning of 11-th to mid 19th century. This time period includes a number of grand minima of solar activity such as Oort, Wolf, Spoerer, Maunder, Dalton and climatic Little Ice Age. Medieval maximum of solar activity has happened during this time interval as well during this period there were variations both in the atmospheric carbon dioxide concentration and in the global temperatures, which were taken into account in the reconstruction of the ¹⁴C production rate in the terrestrial atmosphere. As a result, values of the modulation potential were reconstructed using different temperature proxies.

1. Introduction

Data on relative content of cosmogenic isotopes ¹⁴C and ¹⁰Be obtained by measuring isotope content in tree rings (¹⁴C) and ice cores (¹⁰Be) allow to study variations of the intensity of galactic cosmic rays (GCR) over pre-instrumental epoch – the period, for which there are no direct measurements of the GCR flux. The work [1] presents the results of such a reconstruction for the past 8000 years. It shown that the intensity of the GCR during the Spoerer and Maunder minima of solar activity (SA) was significantly higher than during the Dalton minimum. A similar result for the ¹⁴C isotope production rate in the atmosphere of the Earth has been given in the paper [2]. However, the issue about the impact of climate change on the results of such reconstructions remains open. The necessity to consider the influence of climate change on the ¹⁴C reconstruction has been noted in the paper [3] because the ¹⁴C transfer rate between natural reservoirs is a temperature dependent and this leads to the natural redistribution of carbon dioxide (CO₂) between various reservoirs.

In present work we consider the reconstruction of the heliospheric modulation potential, which describes the variation of GCR intensity during the time interval from the beginning of 11-th century till the mid-19th century. During this epoch the extrema of SA were established, such as Oort (≈1050AD), Wolf (≈1300AD), Spoerer (1400-1510AD), Maunder (1645-1700AD), Dalton (≈1810AD) minima and Medieval maximum, as well as the Little Ice Age (LIA) – the period, during
which there were changes both in the concentration of CO$_2$ in the atmosphere and in the global
temperature. In [4] the reconstruction of the ocean surface temperature (SST) near Antarctica during
the last 12,000 years is presented. As was shown in [4] the reconstruction of the SST during the last 12
millennia demonstrated clearly that decrease of the temperature in the middle of the 2-nd millennium
BC could reach up to 2°C and decline coincided with the Little Ice Age. The authors of the work [5]
also showed that decrease of the global SST took place during second millenium. Such changes of the
oceanic temperature should be taken into account in calculations.

Unfortunately, the accuracy and temporal resolution of the data do not allow us to use them for
detailed calculations. However, taking into account the fact that SST variation coincided with the
global climate change, we may assume that variations of SST are proportional to the variations of
global surface air temperature, which reconstructions have greater accuracy and good temporal
resolution. In this paper we used the various certain temperature reconstructions.

2. Reconstruction of the heliospheric modulation potential based on radiocarbon data

Methods of calculating the heliospheric modulation potential $\varphi(t)$ is described in detail in the works
[2,6], where take into account the influence of the geomagnetic field [7], which counteract to the
penetration of GCR particles in the Earth's atmosphere. The corresponding geomagnetic dipole
moment was submitted in paper [2]. Calculation of the potential $\varphi(t)$ reduces to the solution of the
following equation (see,e.g.[6]):

$$Q = \sum_{i=1}^{2} Y_i(E) J_i(E,\varphi)(1 - f(E))dE,$$

where $Q$ is the 14C isotope production rate in the Earth's atmosphere; $Y_i$ is yield function of 14C isotope
production in the atmosphere [8]; $J_i$ is the spectrum of protons and $\alpha$-particles of the primary cosmic
rays; $f$ describes the influence of the geomagnetic field on the penetration of GCR particles in the
Earth's atmosphere, $E$ is the kinetic energy of the GCR particles (GeV/nucleon). The specific form of
these functions is given in [6].

Reconstruction of the production rate of the cosmogenic isotope 14C (Q) currently is performed by
means of one of the two models. In the first case reconstruction of Q(t) is performed using 3-D model
Bern3D-LPJ [9], which includes the dynamic model of vegetation, oceanic sediments and tree-
dimension model of the ocean.

The second way of Q(t) calculation is use of the five-reservoir radiocarbon model (see, e.g. [10]),
which takes into account the radiocarbon exchange between the atmosphere, biosphere, humus, mixed
and the deep layers of the ocean and this model we used in [11,12]. Also when we reconstruct 14C
production rate we take into account climatic effects – the change of CO$_2$ concentration in the Earth's
atmosphere and global temperature changes. We will use reconstruction of CO$_2$ concentration in the
Earth’s atmosphere according to [13] (fig. 1a), which describes change of this concentration in the
second millennium AD in more detail. This is principally important during the Little Ice Age, when
abundance of CO$_2$ in terrestrial atmosphere dropped. According to this reconstruction sharp decrease
of CO$_2$ during the Little Ice Age started in 1540 and reaches minimum value in 1620. During the
same time (1530-1605) decrease of the relative abundance of the 14C isotope in the atmosphere ($\Delta$14C)
took place [14] (fig. 1b).

It is necessary note that the “classic” five reservoir model needs some modernization in order to
take into account influence of changes of the global temperature on the rate of radiocarbon transition
between the natural reservoirs. This modernization was started in the work [15]. In this work the rate
of 14C transfer from the mixed layer of the ocean and the atmosphere ($\lambda_{\text{mix-oa}}$) was simulated by
expression $\lambda_{\text{mix-oa}}=(1+k\Delta T)\lambda_{\text{mix-oa}}$, where $\Delta T$ is anomaly of the global temperature; $k$
is the temperature coefficient. It is shown that the value of the temperature coefficient $k$ should be $\sim 0.1 K^{-1}$ [15].
In our calculations we considered temperature changes in of the surface layer of the ocean as synchronous with the changes of the surface temperature in the vicinity of the Earth. We will use different temperature reconstructions for the global temperature [16-21]. All these series were averaged over 30 years in order to remove short-term weather variations.

Thus, when we used these temperature reconstructions and the temperature coefficient $k=0.1K^{-1}$, then the change of the rate of transition of the isotope $^{14}C$ from the surface layer to the atmosphere (it is described by the value $k\Delta T$) can reach 3% - 8%. We have noted above that decrease of the temperature of the surface layer of the ocean in the middle of the second millennium AD could reach 1-2°C, while the partial pressure of the carbon dioxide in water increases by ~ 4% when temperature of water increases by 1 °C [22]. That is why variations of the rate of the radiocarbon transition (3% - 8%) from upper layer of the ocean to the atmosphere look like fairly substantiated.

![Figure 1. (a) - Reconstruction of the CO$_2$ concentration in the Earth’s atmosphere according to [13]; (b) – $\Delta^{14}C$ according to [14].](image)

Procedure of calculation of $Q(t)$ is similar to that which was used in calculations performed for the time interval after the end of 14th century AD [12]. The calculation of $\phi(t)$ is performed using the equation (1). In present work we consider 1010 AD as the starting point. This is determined by the data on the variations of the CO$_2$ concentration in terrestrial atmosphere [13] used in calculations. The results of reconstruction of $\phi(t)$ are shown in Figures 2.

One should note, that the initial conditions for equations, describing the five-reservoir exchange system, were chosen proportional to initial conditions (see [10,13]), so that the values of $Q(t)$ during the Dalton minimum coincide with the values obtained by [2].

As it is seen from this Figure, minimum values of the reconstructed modulation potential $\phi(t)$ during the Maunder and Dalton minima are closed when the reconstruction [17,19,21] are used. When the reconstructions [16,18,20] are used the values of $\phi(t)$ during the Maunder minimum are higher.

When the reconstruction of Crowley and Lowery [19] is used the value of the reconstructed modulation potential during the solar minima of Oort, Wolf, Spoerer, Maunder and Dalton can drop down to 0.35, 0.3, 0.15, 0.27 and 0.23 GV correspondingly. During the Medieval maximum of SA the reconstructed values of $\phi(t)$ are quite high (0.4-0.6 GV) when the temperature proxy of Crowley and Lowery [19] is used. In should be noted that the value of the reconstructed modulation potential during Oort minimum of SA was close to 0.2-0.4 GV.

3. Conclusion

Deep minima of the Sun’s activity are clearly observed in all the reconstructions of the solar heliospheric potential obtained in present work. All the reconstructions (besides the reconstruction, obtained using the proxy [21]) show that the mean level of solar activity during the Maunder minimum was higher than during the minimum of Dalton. It should be noted, however, that divergences between
different reconstructions are appreciable. Thus, more precise information about the temporal behaviour of the temperature of the ocean is necessary for more reliable reconstruction of the solar activity in the past.

Figure 2. Reconstructions of heliospheric modulation potential obtained with using the temperature reconstructions after Mann et al. [16] (a), Jones et al. [17] (b), Briffa [18] (c), Crowley and Lowery [19] (d), Esper et al. [21] (e) and Moberg et al. [21] (f)
Acknowledgments
The work of Kuleshova A.I., Kudriavtsev I.V., Nagovitsyn Y.A., Ogurtsov M.G. was partly supported by RFBR (grant No 16-02-00090), and the program of the Presidium of RAS.

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