Influence of Atmospheric Processes on Be-10 atom concentrations

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***Abstract*—In many papers the data on Be-10 concentrations in ice cores have been used to extract the information on cosmic ray fluxes and some characteristics of the interplanetary medium in the past. However, as it is shown below, the influence of atmospheric processes on the precipitation rate of these atoms from the atmosphere to the ground is very essential. The question on the separation of atmospheric influence on Be-10 concentrations in ice cores from other factors is discussed.**

1. Introduction

The cosmic rays in the interactions with air nuclei produce radionuclides Be-10, C-14 and others. These radionuclides fall on the Earth's surface and are accumulated in the ice (Be-10) and tree rings (C-14). It takes about (1-2) years for Be-10 and (5-6) years for C-14. The half-decay periods of these radionuclides are $1.5 \cdot 10^6$ and 5730 years, respectively. The data on Be-10 and C-14 concentrations are widely used to define cosmic ray (CR) fluxes, solar activity levels and so on in the past (see, for example, [1]-[6]).

However, in most of such papers the influence of atmospheric processes on Be-10 and C-14 precipitation is not taken into account. It is difficult to do because in the past the atmospheric conditions, such as snowfall levels, mixing of atmospheric air masses of polar, middle, and equatorial latitudes are unknown.

Below it is shown that similar atmospheric processes are responsible for the temporal changes of Be-10 (and C-14) concentrations observed in ice cores (and tree rings) [6[-[9].

2. About Relationship of Be-10 Data with CR Fluxes

More than 50 years CR fluxes have been measured in the atmosphere. The experimental data obtained show large 11-year variations related with solar activity changes. For example, in the polar atmosphere the 11-year variations of cosmic particles in the absorption curve maximum are ≥ 150%. In the period of 1953 – 1985 we have both sets of the experimental data: Be-10 concentrations in Greenland ice cores and cosmic ray fluxes in the northern polar atmosphere. So, there is a possibility to compare these data. Fig. 1 shows time dependences of Be-10 concentrations in Greenland ice cores and CR fluxes at absorption curve maximum in the northern polar region.

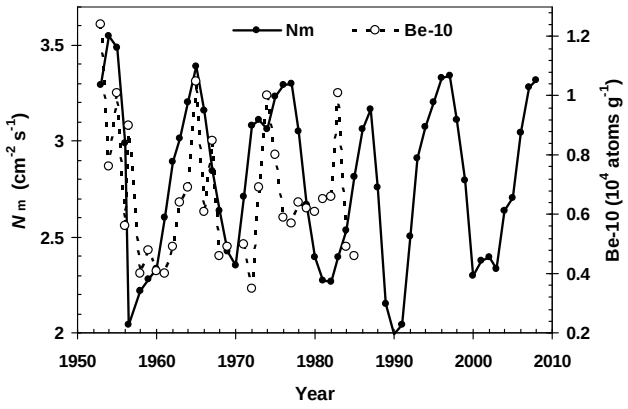

Fig. 1. Time dependences of CR flux at the absorption curve maximum, N_m, in the northern polar atmosphere at the latitude with the geomagnetic cutoff 0.6 GV (dark points and solid curve, left vertical axis, [8]) and Be-10 concentrations in Greenland ice cores (open points and dashed curve, right vertical axis, [5]). Yearly averages are shown.

In Table 1 the correlation coefficient r of Be-10 data with CR fluxes presented in Fig. 1 is given. Two periods are under consideration: 1953 – 1985 and 1953 – 1973. In both cases there are the data on CR fluxes and Be-10 concentrations.

TABLE I
Correlation Coefficient R between Be-10 and CR Data vs. Time – Shift ΔT between Them. Yearly Averages Have Been Used, σ is the Error of R. the Maximum Values of R are Emphasized.

Period of (1953 – 1985)						
Δt, year	-2	-1	0	**1**	2	3
r	0.08	0.31	0.36	**0.47**	0.41	0.17
σ	0.18	0.16	0.16	**0.14**	0.15	0.17
Period of (1953 – 1973)						
r	0.12	0.45	0.53	**0.71**	0.59	0.23
σ	0.22	0.18	0.16	**0.11**	0.15	0.21

For the whole period of 1953 -1986 the correlation of Be-10 data with CR fluxes N_m is rather low, the maximum correlation

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coefficient is equal to $\boldsymbol{r}$ = 0.47 ± 0.14 while the delay time between these data is $\Delta t \approx 1$ year [8]. Although in the atmosphere only CRs produce Be-10 atoms, the relationship of these two experimental data sets is weak. It means that atmospheric processes, such as level of snowfalls, mixing of air masses of polar, middle and equatorial latitudes, rate of exchange of air masses between stratosphere and troposphere, play essential role in the transport of Be-10 atoms from the atmosphere to the ground.

However, for the second period of 1953 – 1973 the maximum value of $\boldsymbol{r}$ is rather high, $\boldsymbol{r}$ = 0.71 ± 0.11 at $\Delta t \approx 1$ year and there are ~11-year changes both in CR and Be-10 data. From this follows that Be-10 nuclides spend ~ 1 year in the atmosphere before precipitation to the ground. As is shown below during this period the influence of atmospheric conditions on Be-10 concentrations was minimal.

3. Comparison of Be-10 and C-14 Sets of Data

Now we have data on Be-10 from Greenland ice cores, from Antarctic ice cores, and C-14 data from tree rings. As in the atmosphere only cosmic rays produce Be-10 atoms and in the past (up to ~ 1900) only cosmic rays produced C-14 atoms, the time dependences of smoothed values of all sets of data have to be alike. One can expect that the CR flux changes will give the same time variations in Be-10 and in C-14 smoothed data (the amplitudes of these variations can be different for these radionuclides). However, if atmospheric factors influence precipitation process of Be-10 and C-14 from the atmosphere to the ground we will have different time dependences in these data sets. In Fig. 2 the time profiles of three sets of data (two for Be-10 and one for C-14) for 1500-1980 are shown.

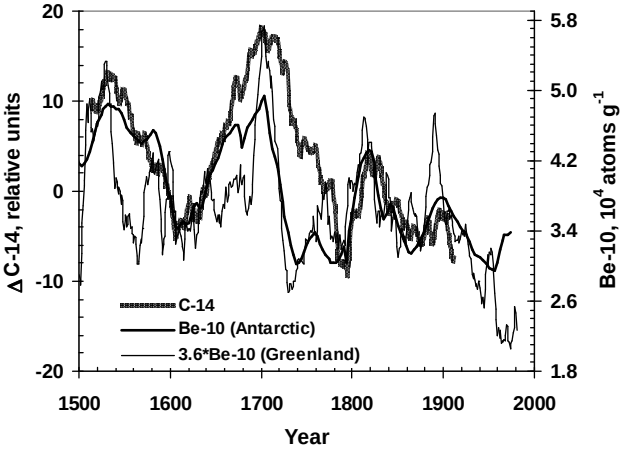

Fig. 2. Time dependences of Be-10 and ΔC-14 concentrations in ice cores and tree rings respectively: Be-10 from the Antarctic ice cores – thick curve and right vertical axis, Be-10 from Greenland ice cores (multiplied by 3.6) – thin curve and right vertical axis, and ΔC-14 from tree rings – dashed curve and left vertical axis. Smoothed yearly average data are given.

The data of Be-10 and ΔC-14 were taken from [2], [3], [5], [10] and were smoothed to correct for the time difference for Be-10 and C-14 between the production of these atoms in the atmosphere and their incorporation into ice cores (Be-10) and tree rings (C-14).

In the data of Fig. 2 a negative trend is observed. There are some periods when the time dependences of all three curves agree with each other rather well, e.g. ~ (1580 – 1640), ~ (1800 – 1880). But in other periods there are also large differences in the data presented. One of them is the large difference between Be-10 concentrations in Antarctic and Greenland ice cores. The Be-10 concentrations in Greenland are lower than in the Antarctic by a factor of ~ 3.6, in spite of the fact that CR fluxes in these regions were the same. From 1963 till present time the CR fluxes measured in the atmosphere at the northern and southern polar latitudes are the same with an accuracy of several percent [11]. Another difference is observed in the Maunder period (1645 – 1715). During this period the Be-10 concentrations obtained in the Antarctic were high, while in Greenland the rise of concentrations started only in ~ 1690. The ΔC-14 data show a wider peak in comparison with the Be-10 data.

All these differences can be explained if one suggests that atmospheric processes have a strong impact on the transition conditions of Be-10 and C-14 atoms from the atmosphere to ice cores and tree rings respectively [6] – [9].

The additional demonstration of essential influence of atmospheric processes on these nuclides is rather high correlation between ΔC-14 and δO-18. Time changes of δO-18 reflect the temperature changes on the Earth. Cosmic rays do not produce O-18 atoms.

If we use the Be-10 and C-14 data sets given above to find CR fluxes in the past, we will have three different sets of cosmic ray fluxes. However, we can find CR fluxes in the past using another method. From 1954 till now we have experimental data on CR fluxes $\boldsymbol{J}$ in the atmosphere. There is a tight relationship between CR fluxes and solar activity (sunspot number $\boldsymbol{R}$). It is expressed as $\boldsymbol{J}(t) = \boldsymbol{J_0}\exp(-\boldsymbol{AR})$, where $\boldsymbol{J}(t)$ is CR flux at time t, $\boldsymbol{J_0}$ is unmodulated CR flux, $\boldsymbol{A}$ is constant. The correlation coefficient between $\boldsymbol{J}$ and $\boldsymbol{R}$ is $\boldsymbol{r}$ = -0.90 ± 0.03. Thus, it is possible to find CR fluxes in the past by using known values of the sunspot number $\boldsymbol{R}$. It was found that for the period from 1500 till 2004 the CR flux with 11-year smoothing was almost constant [8]. Thus, the changes in Be-10 and C-14 data (see Fig. 2) were caused by the changes in the atmospheric conditions (precipitation levels, mixing of air masses and so on). The long-term negative trend observed in the Be-10 and C-14 data could then be explained by the long-term gradual decrease of the CR flux at a rate of about -0.05 %/year caused by a nearby supernova explosion in the past [12].

4. Relationship Between Be-10 Data and Global Temperature of Surface Air

In Fig. 3 the time dependences of Be-10 concentrations in Greenland ice cores and global surface air $\boldsymbol{T}$ are presented [4] and [ftp://ftp.ncdc.noaa.gov/pubdata/anomalies/global_meanT_C.all]. The 5 year smoothed values are shown.

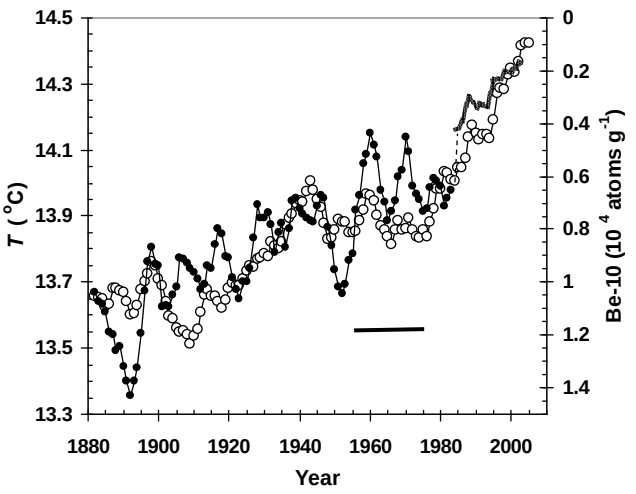

Fig. 3. Time dependences of global surface air temperature $\boldsymbol{T}$ (open points, left vertical axis) and Be-10 atom concentrations from Greenland ice cores (black points, right vertical axis), expected Be-10 concentrations after 1986 (shaded curve in the right upper corner). Black horizontal bar shows the period of 1953-1973.

It is seen that during (1953 – 1973) the value of $\boldsymbol{T}$ was almost constant (see horizontal bar in Fig. 3) and after ~1973 an increase of $\boldsymbol{T}$ took place. During the period of (1953 – 1973) the amplitudes of changes of Be-10 concentrations and CR fluxes were near the ones expected (see Table 2).

TABLE 2

YEARLY AVERAGED VALUES OF MAXIMUM AND MINIMUM CR FLUXES J_{MAX}, J_{MIN} ON THE TOP OF THE ATMOSPHERE IN MINIMA (1954, 1965) AND MAXIMA (1957, 1970) SOLAR ACTIVITY PERIODS AND YEARLY VALUES OF BE-10 CONCENTRATIONS IN GREENLAND ICE CORES ONE YEAR LATER. RATIOS OF THESE VALUES.

CR fluxes $J(E > 100$ MeV), $m^{-1}\ s^{-1}\ sr^{-1}$	n(Be-10), atoms g^{-1}	Ratio of CR fluxes (J_{max} / J_{min})	Ratio of Be-10 (n_{max} / n_{min})
3942 ± 35 (1954, max)	1.01 (1955)	~ 4.6	~ 2.5
854 ± 50 (1957, min)	0.4 (1958)		
3600 ± 30 (1965, max)	1.05 (1966)	~ 2.2	~ 2.1
1645 ± 50 (1970, min)	0.5 (1971)		

As is seen from Table 1 the ratios of CR fluxes (J_{max}/J_{min}) and Be-10 concentrations n coincide more or less with each other. The value of $J_{max}(E > 100$ MeV) for 1954 was obtained from the measurements of ions in the atmosphere [8] and has large uncertainty.

The coincidence of ratios means that during 1954-1970 the influence of atmospheric processes on Be-10 concentrations was minimal, and the 11- year changes in Be-10 data were observed. The amplitudes of changes in Be-10 concentrations are in agreement with the amplitudes of changes in CR fluxes. However, during other periods of time the 11- year changes in Be-10 data were strongly suppressed and they can be found only using the spectral analysis methods.

From Fig. 3 the relationship between Be-10 data and global surface air temperature $\boldsymbol{T}$ can be found for the period of 1880 – 1986: $\boldsymbol{T} = 13.7 \cdot [\boldsymbol{n}(\text{Be-10})]^{-0.028}$ or $\boldsymbol{n}(\text{Be-10})] = 13.7 \cdot (\boldsymbol{T})^{-35.84}$ with the correlation coefficient $\boldsymbol{r} = -0.73 \pm 0.05$. As CR flux was almost the same from 1500 till present time, all changes of Be-10 concentrations were caused by atmospheric processes. From the expression given above the values of $\boldsymbol{T}$ in the past can be recovered from the Be-10 data [9]. Thus, the Be-10 data can be used as a proxy of the global surface air temperature $\boldsymbol{T}$ and the values of $\boldsymbol{T}$ in the past can be recovered from the data on this radionuclide [9]. On the other hand, using the relationship between Be-10 and $\boldsymbol{T}$ data, the Be-10 concentrations in Greenland ice cores can be evaluated from the temperature data for the period of 1986 to present time. For this period the Be-10 data are absent. As it follows from the direct measurements, the CR ray flux in the atmosphere smoothed with 11-year period is almost the same in the period of 1986 - present time [13]. Consequently, the Be-10 concentrations have to be almost constant. But if atmospheric processes influence strongly the transfer conditions of Be-10 atoms from the atmosphere to the Earth's surface, and the global surface temperature changes reflect this influence, then from 1986 till now the Be-10 concentrations will decrease. It is shown by shaded curve in Fig. 3.

5. CONCLUSION

The analysis of the experimental data on CR fluxes in the atmosphere and Be-10 atom concentrations in ice cores obtained during the same period of 1953 -1986 leads us to the following:

- The life - time of Be-10 atoms in the atmosphere is about 1 year and the amount of these atoms transferred to the Earth's surface strongly depends on the atmospheric processes such as precipitation levels, mixing of stratospheric and tropospheric air masses and others. It is the main reason why we have large differences of the values of Be-10 concentrations and their time dependences in the Antarctic and Greenland ice cores.
- The relationship of Be-10 concentrations with the CR fluxes is low. For the period of 1953 – 1986 when there are experimental data on CR fluxes in the atmosphere simultaneously with Be-10 data the correlation coefficient between these two sets of data is $\boldsymbol{r} = 0.47 \pm 0.14$.
- During the period of 1953 -1976 when the atmosphere was more or less quiet we observe the distinct 11 – year solar modulation of Be-10 atom concentrations in Greenland ice cores with the amplitude expected from CR flux modulation.
- There is a relationship between the Be-10 data and the data on global surface air temperature $\boldsymbol{T}$. The Be-10 data can be used as a proxy to evaluate the global surface air temperature in the past: $\boldsymbol{T} = 13.7 \cdot [\boldsymbol{n}(\text{Be-10})]^{-0.028}$.
- Now from Greenland ice cores we have the Be-10 data up to 1986 and there are the data on global surface air temperature $\boldsymbol{T}$ up to now. It is known that for the last ~60 years CR fluxes were constant in time (after smoothing

for the 11-year solar modulation). From the relationship between CR flux and Be-10 concentration ($\boldsymbol{n}$(Be-10)] = $13.7\cdot(\boldsymbol{T})^{-35.84}$) the values of $\boldsymbol{n}$(Be-10) can be found. The calculations show that after 1986 the Be-10 concentrations will decrease in spite of the steady CR fluxes.

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