

CONTENT OF COSMOGENIC ^7Be IN THE AIR LAYER AT THE GROUND AT TEMPERATE LATITUDES

E. A. Buraeva, M. G. Davydov,
L. V. Zorina, V. S. Malyshevskii,
and V. V. Stasov

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The ^7Be content was measured in aerosols (once per week) and precipitation (once per month) was monitored as part of the monitoring of the radioactivity of the atmospheric layer near the ground in Rostov-on-Don in 2001–2005. Data were obtained on the correlations between the ^7Be volume activity in aerosols and the Wolf number, temperature, and amount of precipitation. The highest correlation coefficients were observed during the spring ($k = 1$). It was determined that the volume activity of ^7Be changes in the second half of the 23rd cycle of solar activity, i.e., the yearly average ^7Be concentration increases toward the end of the cycle. Data were obtained on the seasonal dependence of the precipitation density and the volume activity of ^7Be on the meteorological parameters (temperature, amount of precipitation).

Cosmogenic ^7Be ($T_{1/2} = 52.3$ days) forms in nuclear spallation reactions when high-energy protons (~ 1 GeV) when cosmic rays interact with nitrogen nuclei in the stratosphere $^{14}\text{N} + p \rightarrow ^7\text{Be}$ (up to 70–80%) and secondary neutrons with nitrogen nuclei and oxygen in the troposphere $^{14}\text{N} + n \rightarrow ^7\text{Be}$ and $^{16}\text{O} + n \rightarrow ^7\text{Be}$ (up to 20–30%) [1, 2]. During changes in the solar activity (number of sun spots – the Wolf number W) within the 11-year solar cycle and aperiodic bursts of solar activity, the geomagnetic field changes, cosmic rays are deflected and, correspondingly, the ^7Be production rate changes [3]. A decrease of the ^7Be production rate corresponds to an increase of solar activity (increase of the Wolf number) and vice versa, i.e., there is an anticorrelation between the ^7Be content in the atmospheric air and the Wolf number with coefficient $k = -0.81$ according to [4] and $k = -0.83 \pm 0.03$ according to the data in [5]. Over the 11-year solar cycle, the yearly average content at the maximum and minimum differs by approximately 45%. The ^7Be production rate also depends on the geographical coordinates of the observations station because of the effect of the Earth's magnetic field on the cosmic ray distribution.

Long (more than two cycles of solar activity) systematic measurements on the global network of stations must be performed in order to determine reliably the relation between the ^7Be volume activity in the air layer at the ground and the solar activity against the background of variations of a different origin. The results of the determination of ^7Be in the atmosphere in 1974–1999 at 26 stations were analyzed in [3]. The existence of the anticorrelation indicated above, which explains about 54% of all temporal variations of the ^7Be for stations in Australia, New Zealand, and North America and only 18% of the variations for the stations in South America and Antarctica, has been proven.

Long-time measurements (1987–2003) were performed recently at temperate latitudes ($40^\circ 38'$) [6]. Under especially favorable conditions (regularity of measurements of the meteorological parameters, absence of any effect due to some of them, and so forth), a correlation between the ^7Be content and the Wolf number can be determined reliably. Thus, measurements performed under the conditions of a dry and hot climate [7] showed that the changes of the yearly average volume activity of ^7Be depend on the Wolf number (Table 1). A correlation cannot be established under different, less favorable, conditions [8].

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TABLE 1. Yearly Average ^7Be Volume Activity and the Wolf Number in a Dry and Hot Climate

Year	W	q , mBq/m ³
1994	29.9	4.33
1995	17.5	5.86
1996	8.6	6.4
1997	21.5	5.01
1998	64.3	4.55

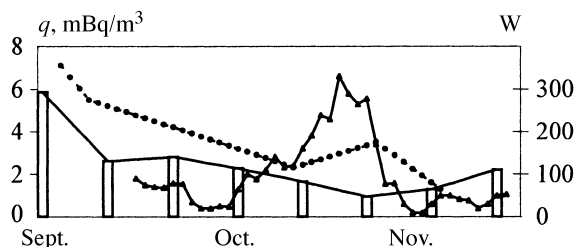


Fig. 1. ^7Be volume activity according to data obtained by the present authors (\square) and in [6] (---) and the number of sun spots (\blacktriangle) in October–November 2003.

Short-time flares with the highest Wolf number can sometimes be manifested as a sharp decrease of the ^7Be content in the atmosphere. Such an effect was observed in [6] (Fig. 1).

Almost immediately after they are formed, the ^7Be nuclei precipitate in submicron-size aerosols, and transport with air masses, settling, and washing out by precipitation determines their subsequent fate. The methods used to determine the life time of aerosols (the period of time during which half of the initial content of the aerosols is removed from the atmosphere) and the results obtained are presented in [9] together with data for other observation points (Greece, Germany, California, Hong Kong). It has been suggested that the data of [9] be divided into two groups: 2.6–15 days (average 8.8 days) for the air layer at the ground and 21–35.4 days (average 28.2 days) for the troposphere. According to other ideas, the first group describes tropospheric and the second stratospheric aerosols. Estimates obtained using the model of [10] give $\tau_r = 24\text{--}30$ days for tropospheric aerosols and $\tau_r = 1$ yr for stratospheric aerosols.

The variations of the ^7Be volume activity in the air layer at the ground depend on the exchange of air masses between the stratospheric and tropospheric reservoirs, dry and wet fallout, and tropospheric processes (vertical transport, advection) [3].

Measurements of the ^7Be content in aerosols (1 per week) and precipitation (1 per month) are performed at the aspiration station of the Research Institute of Physics at Rostov State University in 2001–2005 as part of the monitoring of the radioactivity of the atmospheric layer at the ground in Rostov-on-Don (47°14' NL; 39°42' EL). The location of the station at temperate latitudes with a temperate continental climate and comparatively low precipitation imparts special significance to the systematic monitoring of ^7Be in the atmosphere.

A ventilation setup with a filter consisting of FPP-15-1.7 Petryanov fabric with total area 0.56 m² and a MMN-240 micromanometer were used to obtain the samples. According to the measurements, the air flow rates were approximately 630 m³/h initially (“fresh” filter) and 510 m³/h after 7 days of exposure. The exposed filter was air dried and pressed into 35 mm in diameter and 10–30 mm high pellets. Three or four days after the filter was removed, the γ -ray spectrum was measured in 12–24 h with a Ge(Li) or ultrapure Ge detector of the RÉUS-II-15 setup. ^7Be was determined according to the 477 keV peak. The dust content in air was found according to the mass difference between the exposed and clean filter.

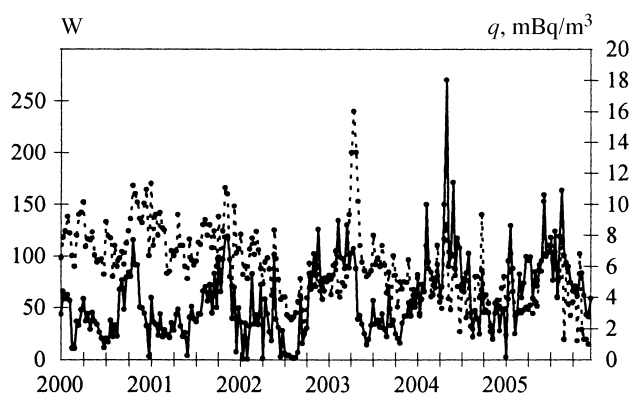


Fig. 2. Correlation between the ^7Be content (—) and the Wolf number (---).

TABLE 2. Correlation Coefficient between the ^7Be Content and the Wolf Number, Averaged over Seasons and Years

Season	2001	2002	2003	2004	2005
Winter	1	0.02	1	0.52	0.75
Spring		0.9	0.99	0.7	0.92
Summer	0.54	0.84	0.33	0.2	0.43
Autumn	0.88	-0.29	0.92	-0.09	0.96
Entire year	0.8	0.37	0.81	0.33	0.76

TABLE 3. Seasonal Average of ^7Be Volume Activity

Year	Winter	Spring	Summer	Autumn	max/min	Average, mBq/m ³	W_{av}
2001	1.53	2.98	4.88	2.12	3.2	2.88	116.8
2002	4.43	3.66	5.07	2.33	2.2	3.82	107
2003	2.01	3.12	5.83	4.02	2.9	3.7	84.8
2004	2.34	3.89	6.43	3.97	2.7	4.15	68.9
2005	3.32	5.72	6.41	3.38	1.9	5.27	54

Analysis showed that the data are insufficient to determine the anticorrelation between the ^7Be volume activity and the solar activity, as done in [3, 5]. An example of the effect of a short-time bright burst of solar activity on the decrease of the ^7Be content in the atmosphere is shown in Fig. 1: after the event on October 29, 2003 with $W_{\text{max}} = 330$ a subsequent decrease of the ^7Be content was observed on October 9, 2003 from 3 to 1.3 ± 0.12 mBq/m³ [6]. Our data show that the ^7Be content decreased from 1.7 to 0.9 mBq/m³. The overall picture of the relation between these two quantities is displayed in Fig. 2. Nonetheless, a positive correlation was established between the volume activity of ^7Be and the Wolf number with averaging over 1 week intervals (Table 2). The volume activity of ^7Be does not react to short- and long-time variations of the Wolf number and the life time of aerosols in the troposphere.

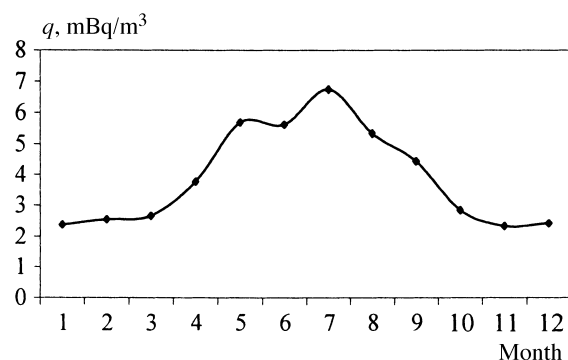


Fig. 3. Seasonal ⁷Be concentration averaged over 5 years.

TABLE 4. Correlation between the ⁷Be Concentration and Temperature

Season	2001	2002	2003	2004	2005
Winter	1	0.99	0.28	0.18	-1
Spring		0.98	0.99	0.99	0.99
Summer	0.94	0.72	0.97	1	-0.57
Autumn	0.78	-0.95	0.97	0.76	0.99
Entire year	0.91	0.44	0.8	0.73	0.1

We were able to establish the dependence of the ⁷Be volume content for the second half of the 23rd cycle of solar activity – its yearly average values increase toward the end of the cycle (Table 3).

The seasonal variation of ⁷Be in aerosols, which is well known for different latitudes and climatic conditions and is associated with the spring rearrangement of the atmosphere in the stratosphere–troposphere system, is quite clearly detected (see Table 3 and Fig. 3). Fourier analysis of the entire set of data over five years confirms the seasonal variation – the period of the first dominant harmonic is 52 weeks.

As a rule, the seasonal variation of the ⁷Be volume activity exhibits a spring–summer maximum and an autumn–winter minimum. Thus, for temperate latitudes (Greece) the summer maximum is 7.29–6.96 mBq/m³ and the winter minimum is 2.75–4.09 mBq/m³ [4]. For our country (Moscow), the spring–summer maximum is 4.3–4.6 mBq/m³ and the autumn–winter minimum is 2.6–3.3 mBq/m³ [8]. Our data show that spring–summer maximum of the ⁷Be volume activity in aerosols is observed yearly (see Table 3) and on the average over the last five years (see Fig. 3). The average ratios of the maximum to minimum values of the seasonal average of the ⁷Be content equal approximately 2.1 (for Moscow 1.6 over 1996–2001 [8]). The five-year average (2001–2005) of ⁷Be volume activity in aerosols is ~3.9 mBq/m³ in Rostov-on-Don and 4.4 mBq/m³ in Moscow.

The salient features of the seasonal variation of the ⁷Be content in aerosols from one year to another are related with the changes in the meteorological conditions (temperature and quantity precipitation). At temperate latitudes, the amount of precipitation has the greatest effect on the ⁷Be concentration [7, 9], and at equatorial latitudes (tropics) the monthly average temperature has the greatest effect [7]. The temperature dependence of the concentration is most clearly determined for the conditions of dry and hot climate (29°23', Kuwait) as determined over a period of five years: it grows from 1.5 mBq/m³ during the winter with +15°C in December to 8–10 mBq/m³ with 40°C in July–August [7]. The correlation with temperature ($k = 0.46$) has also been established at temperate latitudes during the hottest months (at 25–30°C) [4]. The effect of the precipitation amount is manifested much more sharply.

TABLE 5. Correlation between the ^7Be Concentration and the Amount of Precipitation

Season	2001	2002	2003	2004	2005
Winter	-1	-0.67	0.6	0.42	-0.21
Spring		0.98	1	0.9	1
Summer	-0.18	0.38	-0.93	-1	0.62
Autumn	0.3	0.72	-0.83	-1	0.12
Entire year	0.76	0.55	0.6	0.56	0.61

TABLE 6. ^7Be Fallout Density on the Ground, $\text{mBq}/(\text{m}^2\cdot\text{month})$

Year	Winter	Spring	Summer	Autumn	min/max	Average over one year
2001	0.004	0.039	0.175	0.008	41.9	0.057
2002	0.029	0.014	0.034	0.037	2.7	0.028
2003	0.040	0.032	0.103	0.041	3.2	0.054
2004	0.021	0.122	0.058	0.024	5.9	0.056
2005	-	0.020	0.039	-	2	0.029
2001–2005	0.024	0.046	0.082	0.028	11.1	0.045

A dependence of the ^7Be volume activity on the average temperature and precipitation amount should exist at temperature latitudes [4, 8]. The strongest correlation according to our data occurs in the spring and summer – 0.99 and 0.61, respectively (Table 4). For the cold months, it is either weak ($k = 0.29$ – 0.51) or even negative during individual periods (autumn 2002 and winter 2005), but on average over five years it remains strong (0.6). The data for $47^\circ 14'$ NL confirm and substantially supplement the data also obtained for the temperature latitude $40^\circ 38'$ (for the warm months $k = 0.46$) [4].

The data on the correlation between the ^7Be concentration and the amount of precipitation (Table 5) show an especially high positive correlation for the spring months ($k = 0.9$ – 1). As a rule, during all other months there is an anticorrelation. The average correlation over one year is substantial ($k = 0.55$). Wet precipitation is the most effective mechanism for removing ^7Be from the atmosphere. The wash-out coefficient is estimated to be 30–60% and depends on the dispersity of the aerosol and the type of precipitation (snow, rain, downpour, protracted), which lower the ^7Be content almost all year, but the spring maximum is still there [5]. The dependence of the monthly average ^7Be volume activity on the temperature (T , $^\circ\text{C}$) and the amount of precipitation (P , mm/month) for the spring period has the following form according to the results of averaging over a five-year period (in mBq/m^3): $q = 0.2T + 1.6$; $q = 0.2P + 0.9$.

The ^7Be precipitation density averaged over five years on the ground is highest during the spring–summer period, just as the seasonal maximum of its content in aerosols (Table 6).

The generalized results of an analysis of the relation between the ^7Be content in aerosols and precipitation show the presence of anticorrelation with a coefficient ranging from -0.61 to -0.66 (by year). The maximum amount of precipitation, occurring in June–July, decreases the ^7Be concentration in aerosols immediately after its summer maximum in July. On the whole, this is in agreement with the data on the effect of precipitation on the ^7Be content in the atmosphere at temperate latitudes [4, 8].

The opposite relation between the ^7Be content in aerosols and precipitation is due to selective washing out of the atmosphere by precipitation. After falling onto the ground, ^7Be accumulates in the soil–vegetation cover. On the whole, the ^7Be activity is distributed in the biosphere as follows (% of the total activity): stratosphere 60, troposphere 11, on the ground 8, and ocean (top layers) 20 [11]. The world average volume activity of ^7Be in air at the ground is $3 \text{ mBq}/\text{m}^3$.

On the whole, the results of our preliminary analysis of the ^7Be content in atmospheric aerosols and precipitation elucidate the main features of the variation of these quantities and their relation with the regional climatic characteristics [12].

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