

⁷Be atmospheric concentration at mid latitudes (40°N) during a year of solar minimum

E. KOTSOPOULOU and A. IOANNIDOU*

Aristotle University of Thessaloniki, Physics Department
Nuclear Physics & Elementary Particle Physics Division
Thessaloniki 54124, Greece

Abstract

In this paper we present the variation of ⁷Be concentration in the surface air of Thessaloniki, Greece (40°62'N, 22°95'E) over the year 2009, a year of a deep solar minimum, and, as a consequence, a year of maximum concentration of ⁷Be in surface air. The mean annual activity concentration of ⁷Be for the year 2009 was 6.0 mBq m⁻³. The relative variability of ⁷Be surface concentration related to the solar cycle was calculated to be deviated by about 20% from maximum to mean. A positive correlation ($R = 0.97$) was revealed between the activity of ⁷Be and the temperature T (°C), confirming that the increased rate of vertical transport within the troposphere, especially during warmer months, that make descend air masses enriched in ⁷Be down to the surface layer. The anticorrelation ($R = -0.65$) with RH% is due to intense condensation during high relative humidity conditions, which results in increased aerosol particle sizes and as a consequence in higher scavenging rate of aerosols and lower concentration of ⁷Be in the atmosphere. The influence of precipitation on the ⁷Be atmospheric concentration variability was approximately 10%, with greater the influence of rainfall events of low precipitation rate *e.g.* drizzling.

*E-mail: anta@physics.auth.gr

1. Introduction

Cosmic rays interact with Earth's atmospheric nuclei and produce a number of cosmogenic radionuclides [1–3]. The production rate of cosmogenic nuclides depends on the cosmic ray particle flux. The primary cosmic ray flux at the Earth's orbit has two components: galactic cosmic rays (GCR) and solar cosmic rays (SCR). Since the average galactic cosmic ray flux was inferred to be constant within 10% during the last few million years [4], time-dependent changes of the production rate are caused mainly by variations of the geomagnetic field intensity and the solar activity. Solar modulation is the dominant cause of the observed GCR variability. The atmosphere and the Earth's magnetic field, also act as shields against cosmic radiation, leading to a latitudinal dependence of the primary and secondary particle fluxes and consequently of the production rate of cosmogenic nuclides, with higher values around the magnetic poles and lower values in the equatorial region.

Besides the latitude, the cosmic ray flux and the production rate of cosmogenic nuclides depends on the altitude. The production rate begins to increase at the top of the atmosphere, reaches a maximum at a depth between 100–200 g cm⁻² (depending on nuclide and latitude), and finally decreases gradually down to the Earth's surface [5].

Be-7 is a relative short lived ($T_{1/2} = 53.3$ d) naturally occurring radionuclide of cosmogenic origin, which is formed in the upper troposphere and lower stratosphere by spallation reactions of light atmospheric nuclei (nitrogen and oxygen) with cosmic rays [6]. The combined effects of high ⁷Be production rates in the stratosphere (about 70%; [1]) and the relatively rapid removal of aerosol-associated species from the troposphere, produce a stratospheric ⁷Be concentration of about an order of magnitude higher than those just below the tropopause [7]. Because of the thermal structure of the stratosphere and its separation from the troposphere by the tropopause, the residence time of aerosols in the stratosphere is substantially longer (about 1-2 years) than in the troposphere, where it is on the order of week [8].

Once it is formed, it is rapidly associated with submicron aerosol particles and participates in the formation and growth of the accumulation mode (from 0.07 to 2 μm) aerosols, which is a major reservoir of pollutants in the atmosphere. Following its production, this isotope condenses on the aerosol particles, and the fate of ⁷Be will become the fate of the carrier aerosols [9]. ⁷Be is one of the most investigated radionuclides in the Earth's atmosphere. It is a most important isotope in studying atmospheric processes [10] because of its convenient half-life and sufficiently detectable

γ -radiation ($E_\gamma = 477$ keV, 10.4% emission probability), which has served for studying precipitation scavenging [11], vertical and horizontal removal of air masses [12], aerosol transit and residence times in the troposphere [8].

From year 2000 to 2007, the solar activity varied from the maximum to the minimum. Sunspot minimums come along every 11 years, therefore, it is expected for the Sun to undergo minimum solar activity on a regular basis. 2008 was considered a very deep solar minimum; however, sunspot counts for 2009 have dropped even lower. This was the quietest sun seen in almost a century. Now, during 2010 solar cycle corrects itself and solar activity increases towards the next maximum. In particular, the temporal trends of the recent solar activity could be determined by simply measuring the daily ^7Be concentrations in the ambient air. An anti-correlation is expected between the production rate of cosmogenic nuclides and the sunspot number [13, 14]. Hence, our observations should be advantageous in investigating the current issue of the unusually long calm period of solar activity during 2009 [15].

The objective of this work is to define the concentration of ^7Be in the region of Thessaloniki, Greece (40° N) during a year of deep solar minimum and to calculate the relative variability of ^7Be surface concentration from maximum to mean due to the solar modulation. During a year of minimum solar activity, maximum concentrations of ^7Be are recorded in surface air and can reveal easily the differences in ^7Be fluctuations due to any meteorological and seasonal variation. The influence of the different meteorological conditions and especially the influence of temperature, relative humidity and the wet precipitation is examined.

2. Sampling procedure — instrumentation

Beryllium-7 atmospheric concentration was measured by air sampling; using Staplex high-volume air samplers with Staplex type TFAGF 810 glass-fiber filters $8'' \times 10''$, having 99.28% collection efficiency for particles as small as $0.3 \mu\text{m}$. This design involves a regulated airflow rate of $1.7\text{--}1.92 \text{ m}^3 \text{ min}^{-1}$ ($60\text{--}68 \text{ ft}^3 \text{ min}^{-1}$). The length of each collection period was 24 h. Air samplings were carried out once a week on the roof (20 m above the ground, and 52 m a.s.l.), at the Faculty of Science building in the center of the city of Thessaloniki, Greece.

After the collection procedure, the filters are folded and compressed by means of hydraulic press at up to 3 tons to give a cylinder 5.8 cm diameter and 2 mm height. All the samples were measured for ^7Be

activity ($E_\gamma = 477$ keV) using a high resolution (1.9 keV at 1.33 MeV), low-background HPGe (high purity germanium) detector with 42% relative efficiency. The 1σ counting uncertainties for ${}^7\text{Be}$ measurements were almost always smaller than 8%. Blank filters were regularly checked.

3. Results and discussion

3.1. ${}^7\text{Be}$ concentration levels in surface air

Weekly measurements of ${}^7\text{Be}$ activity concentration on aerosol particles were performed at ground level air in Thessaloniki, Greece during the year 2009. Aerosol sampling started on January 2009. The mean activity concentration of ${}^7\text{Be}$ in surface air has been found to be 6.0 mBq m^{-3} .

The variability of yearly ${}^7\text{Be}$ concentration due to solar modulation was calculated. The mean annual activity concentration of ${}^7\text{Be}$ during the year 2009 was 6.0 mBq m^{-3} . This value is 20% higher than the typical mean value of 5.0 mBq m^{-3} for our latitude (40°N) [16]. This variability of ${}^7\text{Be}$ concentration is due to solar modulation. This result is in a good agreement with results reported from other investigators [17, 18].

The concentration of ${}^7\text{Be}$ in surface air fluctuates considerably. The ${}^7\text{Be}$ weekly concentration values showed a great variability ranging from 0.9 to 14.6 mBq m^{-3} . The highest value was observed in June and the lowest in December. The variability is mainly due to local prevailing meteorological conditions of the atmosphere during the sampling period. Since the day-by-day concentrations of ${}^7\text{Be}$ in surface air show strong variations due to interactions on daily or even shorter time scales, considering the mean monthly concentration, these variations are minimized. Averaging the data of ${}^7\text{Be}$ atmospheric concentration on a monthly basis the mean monthly concentration of ${}^7\text{Be}$ over a year is calculated.

Figure 1 presents the mean monthly atmospheric concentration of ${}^7\text{Be}$ over the year 2009. From Fig. 1 it is evident that the monthly atmospheric concentrations of ${}^7\text{Be}$ in surface air over 2009 varied by a factor of 3 during the year, showing a seasonal trend with the highest values in the summer months (up to 14.6 mBq m^{-3} during June) and the lowest ones in the winter period (0.9 mBq m^{-3} during December). Also relative high values were observed during spring period. This is a typical seasonal ${}^7\text{Be}$ profile for Thessaloniki, Greece (40°N). Atmospheric processes and meteorological parameters that may contribute to these variations are discussed below.

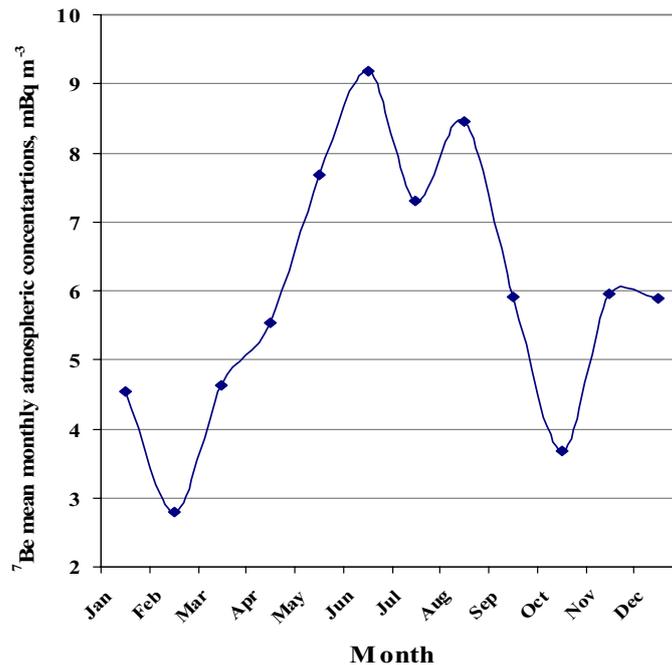


Fig. 1: Mean monthly atmospheric concentration of ⁷Be during the year 2009 at Thessaloniki, Greece 40°N.

3.2. ⁷Be concentration levels in surface air and the influence of T (°C)

The highest ⁷Be activity values are observed during summer, which can be explained by the solar heating of the atmosphere. The solar heating of the surface of the Earth has a result of heating of air masses that are in contact with the ground surface. Cooler air sinks, displacing the warm, less dense air and forcing it upward. This new cold air becomes warm and is forced upward again. A convective circulation is produced, carrying surface air upward, bringing downward air from higher levels [19]. This convective circulation is then connected with the higher ⁷Be activity concentration in surface air, described by the positive correlation between the activity of ⁷Be and the temperature $T(^{\circ}\text{C})$.

Regression analysis shows that the correlation coefficient between the mean monthly activity concentration of ⁷Be and the temperature $T(^{\circ}\text{C})$ is 0.97 and the significance of the regression is given by $p < 0.0001$ (Fig. 2).

The sporadically observed high values of ⁷Be concentrations in spring are connected with stratospheric intrusions during tropopause folding events.

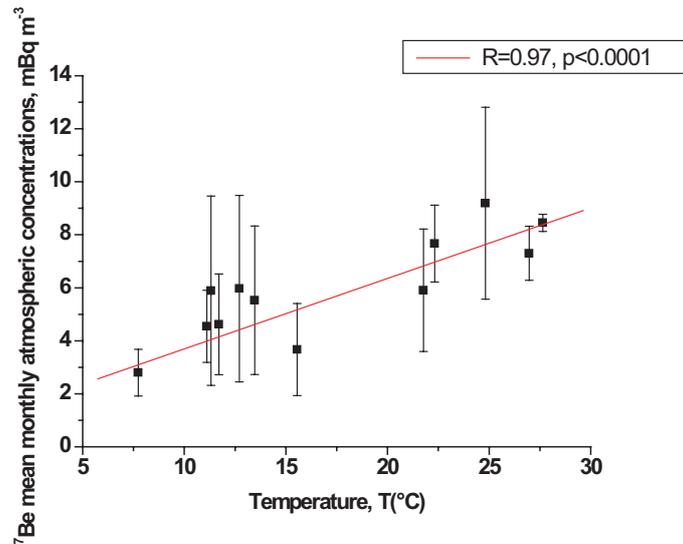


Fig. 2: Mean monthly atmospheric concentration of ${}^7\text{Be}$ vs. temperature, $T(^{\circ}\text{C})$.

The combined effects of high ${}^7\text{Be}$ production rates in the stratosphere (about 70%; [1]) and the relatively rapid removal of aerosol-associated species from the troposphere, produce a stratospheric ${}^7\text{Be}$ concentration that is about an order of magnitude higher than those just below the tropopause [7]. Consequently, the stratosphere-troposphere exchange of air masses seems to result in a significant increase of ${}^7\text{Be}$ in the troposphere during the spring period.

3.3. ${}^7\text{Be}$ concentration levels in surface air and the influence of RH%

A negative correlation coefficient was found between the mean monthly activity concentration of ${}^7\text{Be}$ and the relative humidity (RH%). The correlation coefficient between the mean monthly activity concentration of ${}^7\text{Be}$ and RH (%) is -0.65 and the significance of the regression is given by $p < 0.02341$ (Fig. 3).

The most probable explanation for this anti-correlation is that the condensation during high relative humidity conditions becomes more intense, resulting in increased particle sizes of atmospheric aerosols. But, greater aerosol particle sizes means higher scavenging rate of aerosols and as a result lower activity concentration of ${}^7\text{Be}$ in the atmosphere.

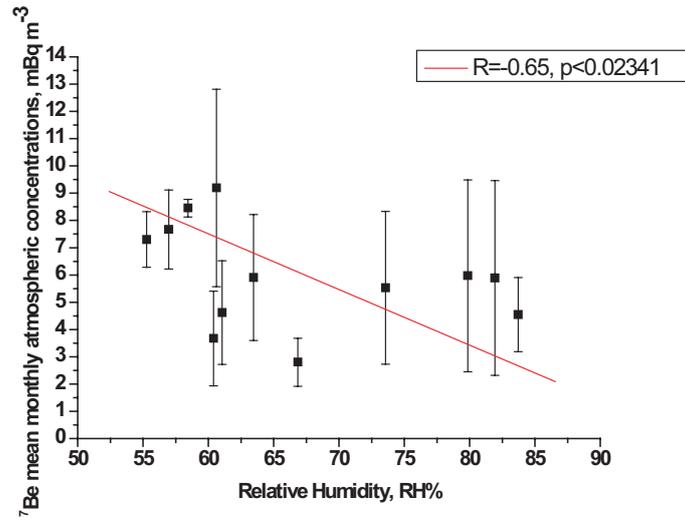


Fig. 3: Mean monthly atmospheric concentration of ${}^7\text{Be}$ *vs.* relative humidity RH%.

3.4. ${}^7\text{Be}$ concentration levels in surface air and the influence of precipitation

The percentage of rainy days, including drizzling, during the sampling period was on the average 13%. The mean activity concentration of ${}^7\text{Be}$, excluding the values during rainfall events, is equal to $6.7 \pm 2.7 \text{ mBq m}^{-3}$, that means 10% higher than the mean activity concentration of ${}^7\text{Be}$ for year 2009, a year of maximum ${}^7\text{Be}$ concentrations and minimum sunspot number. Therefore, the yearly variation in the ${}^7\text{Be}$ concentration is mainly caused by the variation in the ${}^7\text{Be}$ production rate and, hence, by the solar modulation of cosmic rays.

Strong rainfall events during the sampling period result in decreased activity concentrations in the surface air. Low precipitation rates as *e.g.* drizzling result in higher decreased surface air activity concentration [20]. However, the removal of ${}^7\text{Be}$ from the atmosphere by rainfall events seems to be stopped immediately after the event and the ${}^7\text{Be}$ concentration in air is reestablished rapidly. Hotzl and Winkler [21] and Duenas *et al.* [22], also observed no correlation between the ${}^7\text{Be}$ atmospheric concentration in surface air and rainfall.

4. Conclusions

In this paper we presented the variation of the ^7Be concentration in surface air at Thessaloniki (latitude 40°N) during the year 2009. It was a year of a deep solar minimum and, as a consequence, a year of maximum concentrations of ^7Be . For first time in our region of investigation (Thessaloniki, Greece), we recorded values as high as 14.6 mBq m^{-3} . The mean annual activity concentration of ^7Be during the year 2009 was 6.0 mBq m^{-3} . This value is 20% higher than the typical mean value of 5.0 mBq m^{-3} for our latitude (40°N). This variability of ^7Be concentration is due to solar modulation.

The atmospheric concentration of ^7Be shows strong seasonal trends with the highest values being observed in summer and the lowest in winter. The highest observed values during summer are correlated with the vertical removal of air masses within the troposphere, which is stronger during summer period carrying surface air upward and bringing downward air from higher levels enriched in ^7Be , described also by the positive correlation between the ^7Be activity and the temperature $T(^{\circ}\text{C})$.

The observed anti-correlation between the mean monthly activity concentration of ^7Be and the relative humidity RH% might be due to that condensation becomes more intense during high relative humidity conditions, resulting in increased particle sizes of atmospheric aerosols, causing higher scavenging rates of aerosols and, as a result, lower activity concentration of ^7Be in the atmosphere.

No correlation was found between the mean monthly concentration of ^7Be and the amount of precipitation.

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