Test of production models for Beryllium cosmogenic radionuclides in the Earths atmosphere

Gennady A. Kovaltsov*, Ilya G. Usoskin†

*Ioffe Physical-Technical Institute, St.Petersburg, Russia
†Sodankylä Geophysical Observatory (Oulu unit), FIN-90014 University of Oulu, Finland

***Abstract*. Cosmogenic nuclides are produced by cosmic rays in the atmosphere and used in many research applications, such as paleoclimatology, solar activity reconstructions, dating methods, etc. For these purposes, a precise computational model is needed to account for complicated production and transport of the isotopes in the Earths atmosphere. However, large uncertainties still exist between different models, making scientists to often use empirical regression relations instead of physics-based models. Here we present the results of a direct test of numerical production models for cosmogenic radionuclides, which are formed as a result of spallation reactions in the Earths atmosphere: ^{7}Be and ^{10}Be. We perform detailed comparison with the experimental data available and conclude that the Oulu CRAC model adequately reproduce the overall isotope's production.**

***Keywords*: cosmic rays, cosmogenic isotope, atmosphere**

I. Introduction

Cosmogenic isotopes – radionuclides produced in the Earth's atmosphere by cosmic rays – form an important tool for modern science, with special interest to beryllium isotopes ^{7}Be and ^{10}Be [1] which are produced in spallation reactions of atmospheric oxygen and nitrogen caused by cosmic rays. Several numerical models describing production of cosmogenic isotopes have been developed and used during the last decades (e.g., [2], [3], [4], [5], [6]). However, large uncertainties (up to a factor of two) exist in the modeling (see, e.g., discussions in [6], [7]) which makes a direct application of the models difficult and leads to often used regression studies, where an empirical relation is used instead of a full physics-based model. Accordingly, it is crucially important to test and/or calibrate the existing and newly developed numerical models of cosmogenic isotope production using the available direct measurements. Here we perform such a test for a recent CRAC model of Beryllium isotope production in the atmosphere [6] using fragmentary experimental data relevant for such a purpose.

II. Numerical model of Beryllium production

The production rate of ^{7}Be and ^{10}Be in the atmosphere was computed by a recent numerical CRAC model, which is based on detailed Monte-Carlo simulations, using CORSIKA [8] and FLUKA [9] numerical packages, of the nucleonic-muon-electromagnetic cascade initiated by cosmic rays in the Earth's atmosphere. All the details of the model can be found elsewhere [6]. The 3D×time production rate Q of ^{7}Be in the atmosphere can be computed as a function of the altitude h, geographical longitude λ, latitude ψ, and time t as

$$Q(h,\lambda,\psi,t) = \int_{E_c(\lambda,\psi)}^{\infty} Y(h,E)\cdot S(t,E)\cdot dE, \quad (1)$$

where $Y(h,E)$ is the ^{7}Be yield function at altitude h, provided by the CRAC model; $S(t,E)$ is the differential energy spectrum of cosmic rays on the Earth's orbit outside the geomagnetosphere; and integration is over the kinetic energy E of primary cosmic rays above the energy E_c corresponding to the local geomagnetic cutoff. The model can deal with both galactic cosmic rays, which are always present in the near-Earth space, and transient solar energetic particle (SEP) events, via applying the appropriate energy spectrum S in the equation. Digital tables of the ^{7}Be yield function are available from [6]. Cross-sections of the Beryllium isotope production on oxygen and nitrogen targets were adopted from ([10], [11], [5], [12]). We used the force-field approximation of the galactic cosmic ray spectrum [13]. The geomagnetic field was estimated from the IGRF-10 (10-th generation of the International Geomagnetic Reference Field, http://modelweb.gsfc.nasa.gov/magnetos/igrf.html) model for the corresponding time epoch. Computations of the ^{10}Be isotope were done in a similar manner, only changing the yield function Y.

A result of computation using the CRAC model (integral column production of ^{10}Be as a function of the geomagnetic rigidity cutoff) is shown in Fig. 1 along with some other model results. The results of different models differ quite a bit from each other in both the absolute level and the latitudinal profiles. Note that one of the most often used models MB99 [3], which is the lowest one in the Figure, "shows a tendency of the simulations to underestimate observed deposition fluxes and atmospheric concentrations" [14]. The uncertainty may be up to a factor of two. This emphasizes the existent problem with the production model normalization and a need for an independent test of the model results.

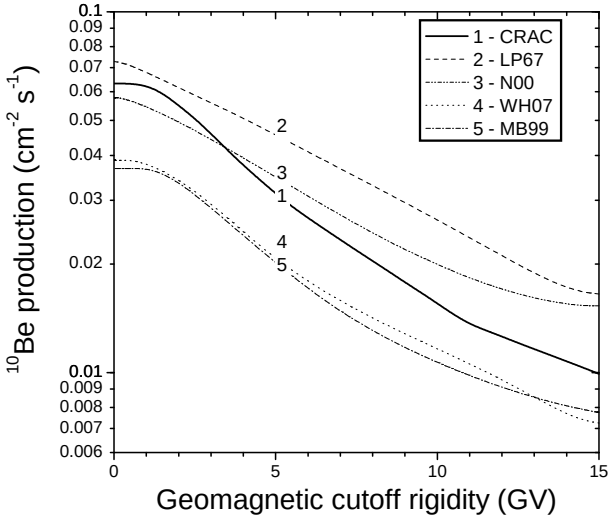

Fig. 1: Dependence of the column integral production of ^{10}Be on the geomagnetic cutoff rigidity for a medium solar activity. Models, as numbered in the legend are: CRAC – [6], LP67 – [2], N00 – [4], WH07 – [12], MB99 – [3].

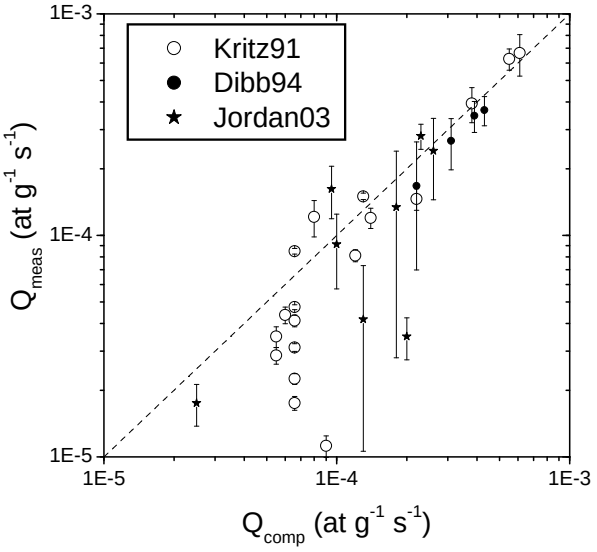

Fig. 2: Scatter plot of modeled vs. computed from measurements, assuming the equilibrium conditions, ^{7}Be production rate in the atmosphere. Different symbols correspond to data from Kritz et al. [21], Dibb et al. [22] and Jordan et al. [23], as denoted in the legend.

III. Comparison with observations

A. Isotope ^{7}Be

The most direct comparison would be with measurements of the production rate of the isotope. One such experiment [15] has been performed in 1959, when a sealed tank filled with oxygen target was exposed to cosmic rays at Echo Lake in Colorado (h =685 g/cm^2). The average measured production rate of ^{7}Be was $9 \cdot 10^{-6}$ at [g target O]$^{-1}$ s^{-1}. Using the appropriate parameters (only oxygen target, $h = 685$ g/cm^2, $P_{\rm c} = 3$ GV, $\phi \approx 1300$ MV) we have obtained the expected production rate of $8 \cdot 10^{-6}$ at [g target O]$^{-1}$ s^{-1}. Thus, the model result agrees well with the direct measurement of ^{7}Be production rate in the troposphere. Next we compare in Fig. 2 some results of air-borne measurements of the ^{7}Be concentrations (converted into the production rate assuming the equilibrium between decay and production) compared with the CRAC model prediction for the same conditions (h, $P_{\rm c}$ and ϕ) taken individually for each measurement. The agreement is very good in the stratosphere, where the concentration of ^{7}Be is expected to be close to the equilibrium, since the isotope's residence time is longer than the decay time. In the troposphere, however, ^{7}Be is quickly washed out leading to the residence time shorter than the decay time. Accordingly, the measured concentration is lower than the equilibrium one, and the difference depends on location and season [16]. A detailed comparison for the troposphere can be performed only by taking into account realistic 3D transport of air masses ([17], [18], [19]). Such a comparison has been done in [20], where the computed (considering the full 3D air transport) concentration of ^{7}Be has been compared with precise

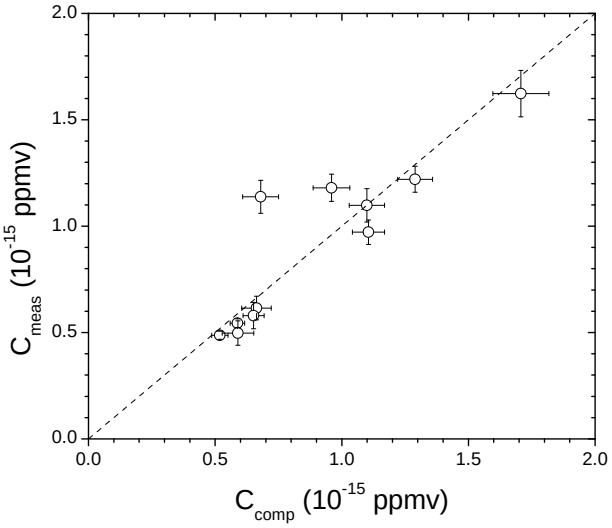

Fig. 3: Scatter plot of modeled vs. measured concentrations of ^{7}Be production rate in the atmosphere (see [20] for details).

measurements near ground in different sites around the globe (Fig. 3). The agreement between data and simulation results is pretty good, and yields $C_{\rm meas} = [0.96 \pm 0.04] \times C_{\rm comp}$ in a wide range of the values.

Another test for the tropospheric concentration of ^{7}Be is related to measurements in the rain water in a region with high level of precipitation, which quickly washes out almost all isotope atoms produced in the troposphere [19]. Several measurements of ^{7}Be content in the rain water have been performed in 1956–1959 in two Indian sites - Kodaikanal ($P_{\rm c} \approx 16$ GV, about 175 cm rainfall)

and Bombay ($P_c \approx 15$ GV, about 100 cm rainfall) [24], with the measured ^{7}Be flux being $1 \cdot 10^{-2}$ and $9 \cdot 10^{-3}$ [at cm^{-2} s^{-1}], respectively. The corresponding CRAC model result is $8.5 \cdot 10^{-3}$ [at cm^{-2} s^{-1}], assuming quick removal of the ^{7}Be atoms [25] which eventually appear in the rain water.

B. Isotope ^{10}Be

Because of the long half-life, it is hardly possible to evaluate the ^{10}Be production rate directly from the atmospheric measurements as done for ^{7}Be isotope. However, several direct production experiments have been performed ([26], [27]), where the isotope's concentration has been measured in a sealed water tank exposed to cosmic rays for one-two years. This gives a chance to directly test our model by considering the production of ^{10}Be only on oxygen. A series of measurements of ^{10}Be in water tanks at different altitudes in two US sites (Echo Lake, 1016 g/cm^2 and La Jolla, 693 g/cm^2) [26] corresponded to moderate and high solar activity. We adopted the values of production rate, corrected for shielding, from their Table 3. Another series of measurements of ^{10}Be in sealed water tanks at different altitudes in French Alps (Mont Blanc 570 g/cm^2, l'Aiguille du Midi 644 g/cm^2, and High-school 960 g/cm^2) [27] corresponds to moderate solar activity. The production rate of ^{10}Be in water was computed as the measured concentration, corrected for shielding, background and transportation/laboratory environment and divided by the exposition period. For each measurement we have performed the corresponding computations by our CRAC model, using the actual parameters (altitude, geomagnetic cutoff and the modulation potential over the period of exposition) and assuming a thin target production of ^{10}Be in water. The results are summarized in Fig. 4, which shows both measured $Q_{\rm meas}$ and the corresponding computed $Q_{\rm comp}$ values. One can see that the model results perfectly match 10 out of 11 measured production rates for a wide range of conditions, from sea-level to high altitude ($h = 570$ g/cm^2) and solar modulation. The only disagreement is observed for the High-school site at 960 g/cm^2. We note that measurements at low altitudes are more difficult because of the orders of magnitude lower production rate (see, e.g., discussion in [27]).

Thus, our model agrees with direct measurements of ^{10}Be production rate in a water target, $Q_{\rm meas} = [0.93 \pm 0.04] \times Q_{\rm comp}$ The agreement is perfect (within a few percent) at mountain altitudes in a wide range of solar modulation parameters and is less clear for the sea level.

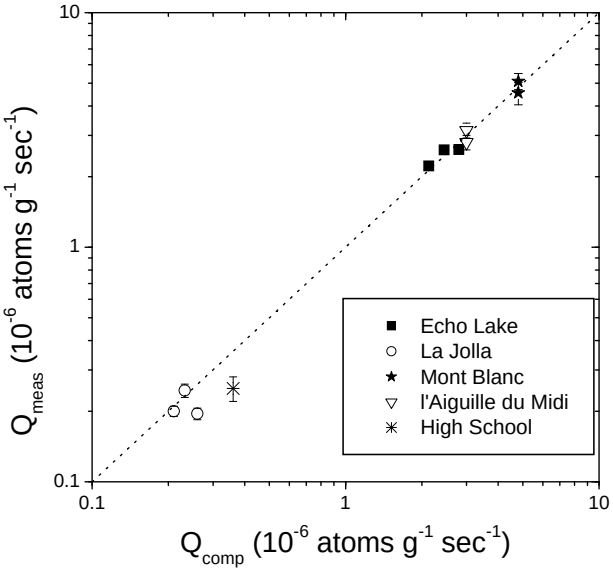

Fig. 4: Scatter plot of measured vs. computed production rates of ^{10}Be in water target. Data for Echo Lake and La Jolla are from ref. [26], data for Mont Blanc, l'Aiguille du Mudi and High School from ref. [27].

IV. CONCLUSIONS

We have performed a detailed comparison between the yield of a numerical CRAC model [6] of cosmogenic Beryllium isotope production with direct and indirect actual measurements. The direct test, using the results of dedicated experiments to measure the isotope's production rate in isolated oxygen targets (water tanks) suggests that the CRAC model correctly (within a few percent) describes the production of both ^{7}Be and ^{10}Be at different conditions. Applying the model results of the ^{7}Be production to the stratosphere we also found a good agreement with the direct air-borne concentrations of the isotope, assuming the equilibrium conditions. In the troposphere, the computed flux of precipitating ^{7}Be agrees well with the direct measurements of the isotope's concentration in rain water in Indian regions of heavy monsoons.

We note that direct measurements of the tropospheric isotope's concentration do not agree with the corresponding production rates, assuming the equilibrium conditions. However, when considering the actual transport of air masses and decay of the isotope, we came to the nearly perfect agreement with the real data. This means that in the troposphere not only production but also transport of Beryllium from other sites and latitudes play a crucial role.

Concluding, the bulk of different independent tests, performed here, suggests that our CRAC model correctly simulated the production of the Beryllium isotope in the atmosphere, in a wide range of parameters: from the ground level up to the upper atmosphere, and from low to high solar activity. Thus, the CRAC model can be regraded for forthcoming studies as fully verified and calibrated. Other numerical models are needed to be tested in a similar manner.

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