ICRC'07 Mérida, México

Long-term Variations in Cosmogenic Be-7 Concentrations with the 11-year Cycle of Solar Activity

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Abstract: Be-7 radionuclide is produced by galactic cosmic-ray interactions with atmospheric nuclei. We analyzed long-term variations (1983-2006) in surface Be-7 concentrations in Japan (geomagnetic latitude 25N) to study an influence of the solar activity. Be-7 concentrations in surface air depend on a production rate of Be-7 and a transport process in the atmosphere. The production rate is inversely correlated with the solar activity, while the transport in the atmosphere is affected by air mass motions. The present result indicated that the surface Be-7 concentrations are anticorrelated with the 11-year cycle of solar activity and the air mass motions do not essentially affect the Be-7 variations.

Introduction

Be-7 radionuclide (half life 53.3 days) produced by cosmic rays in the Earth's upper atmosphere plays a role of a tracer for a study of variations in the cosmic-ray flux. The cosmic-ray flux is well known to correlate inversely with the solar activity, indicating that the Be-7 production rate decreases with an increase of the solar activity. Since Be-7 can not be directly measured in the upper atmosphere, the Be-7 production rate is estimated from the surface Be-7 concentration. The surface Be-7 concentrations depend on not only the Be-7 production rate but also atmospheric motions.

In this paper we analyzed long-term variations in the surface Be-7 concentrations measured in Japan in 1983-2006 and studied a correlation between the Be-7 concentrations and the 11-year cycle of solar activity. Further, we discussed an influence of the atmospheric motions that bring the Be-7 borne aerosol particles from the upper atmosphere to the surface.

Experiment of Be-7 Concentrations

About 70 % of Be-7 is produced in the lower stratosphere and about 30 % in the upper troposphere [1], [2], [3], [4]. Be-7 is attached to a small aerosol particle and brought to the surface by atmospheric motions. Be-7 borne small particles were continuously collected with a high-volume air sampler and the Be-7 concentration is determined from a count rate of Be-7 γ-ray line at 478 keV measured with a high-resolution Ge spectrometer [5].

The surface Be-7 concentrations in Japan were measured by Megumi et al. (1983-1997) [6], Nagai (1997-2000) [7], and Yoshimori (2002-2006) [8]. Unfortunately there is no data in 2001 in Japan. We show long-term variations in the surface Be-7 concentrations (upper) and sunspot number (lower) in 1983-2006 in Figure 1. It indicated the maxima of Be-7 concentration around 1987 and 1997 and minima around 1990 and 2002. These maxima and minima coincide with the solar minimum and maximum periods, respectively. We find the surface Be-7 concentrations inversely correlated with the sunspot number.

Simulation of Be-7 Production Rate

We simulate the variations in Be-7 production rate in Japan (cosmic-ray cutoff rigidity 10 GV) using the revised Be-7 production process [2]. Galactic cosmic rays develop the nuclear cascade and produce a number of secondary protons and neutrons in the atmosphere. The neutron flux is larger by two orders of magnitude than the proton flux. Be-7 is mainly produced from nuclear interactions of secondary neutrons of less than a few hundred MeV with atmospheric nitrogen and oxygen nuclei. One can calculate the altitude dependence of the Be-7 production rate using the energy spectrum of secondary neutrons at various altitudes. The production rate peaks around 150 g cm^{-2} and most Be-7 are produced in lower stratosphere and the remaining is in the upper troposphere. Here we simulate the Be-7 production rate

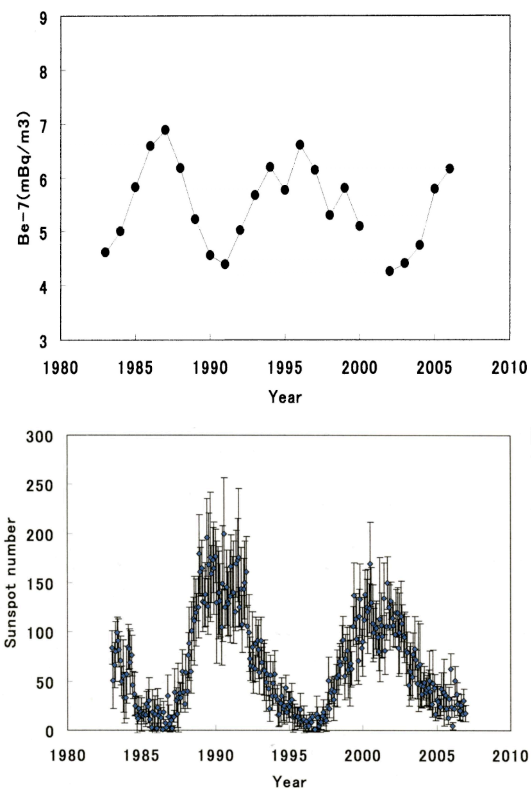

Figure 1: Variations in the surface Be-7 concentration and sunspot number in 1983-2006.

at geomagnetic latitude 30 degree (cutoff rigidity 10 GV) assuming (1) the energy spectra of galactic cosmic rays that vary with the solar activity, (2) the yield of Be-7 nuclei per nuclear reaction, (3) the probability that particle produces nuclear interaction before the threshold energy by ionization loss and (4) the probability of escape of Be-7 to interplanetary space.

The energy spectrum of cosmic rays in the vicinity of the Earth varies with the solar activity. Here the so-called force free model [9], [10] is assumed as the solar modulation process. According to this model, the energy spectrum is characterized by a solar modulation parameter that is 400 MeV in the solar minimum and 1200 MeV in the solar maximum. It is empirically available from the relation between the neutron monitor count rate at Climax (geomagnetic cutoff 2.99 GV) [11]. Variations in the solar modulation parameter are shown in Figure 2.

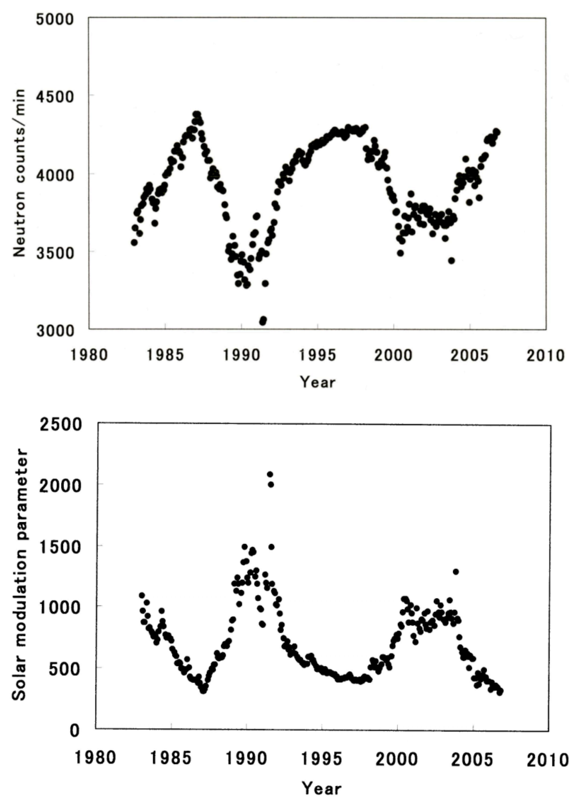

Figure 2: Variations in the neutron monitor count rate at Climax (upper) and solar modulation parameter (lower) in 1983-2006.

The modulated energy spectrum of galactic cosmic ray protons is given by

$$F(E, \phi) = CE(E + 2mc^2)(E + x + \phi)^{-2.5} \cdot (E + \phi)^{-1} (E + 2mc2 + \phi)^{-1}$$

where $C = 1.244 \times 10^6 /\mathrm{cm}^2$ s MeV is the normalization factor, E is the proton energy, $x = 780 \exp(-2.5 \times 10^{-4}E)$ (MeV), ϕ is the solar modulation parameter (MeV) and mc^2 is the proton mass energy (938 MeV). We plot the modulated energy spectra of galactic cosmic ray protons for the solar modulation parameters of 400, 600, 800, 1000 and 1200 MeV in Figure 3.

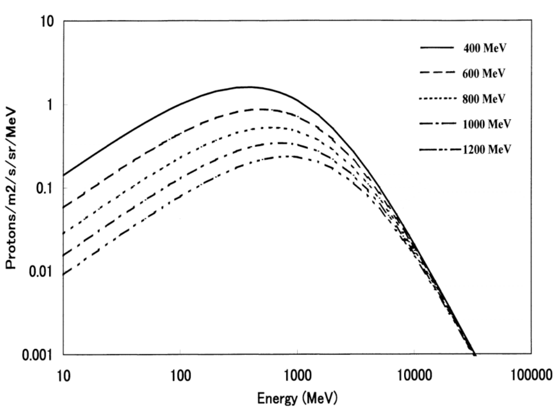

Figure 3: The modulated energy spectra of galactic cosmic ray protons for the solar modulation parameters of 400, 600, 800, 1000 and 1200 MeV.

Variations in the yearly average Be-7 production rate (solid circle) in 1983-2006 are shown in Figure 4. The variations in Be-7 production rate are inversely correlated with the solar activity. We plot the present data of yearly average Be-7 concentrations (open square) in Japan in Figure 4. There are similar variations between the simulated Be-7 production rate and measured Be-7 concentration. A ratio of the Be-7 production rate in the solar minimum to that in the solar maximum is 1.3-1.4. This ratio is due to the variations in the galactic cosmic ray flux between the solar minimum and maximum periods.

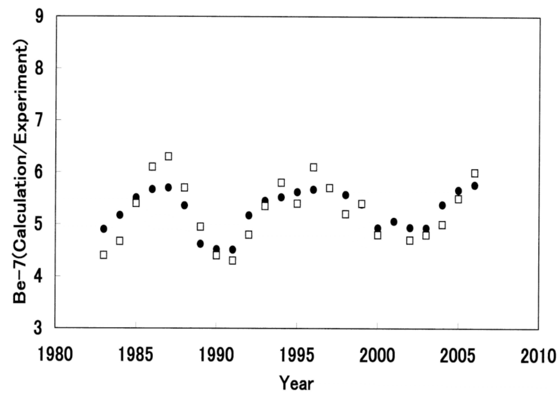

Figure 4: Variations in the simulated Be-7 production rate (solid circle) and the measured Be-7 concentration (open square) in 1983-2006.

Discussion

We plot the Be-7 production rate and the Be-7 concentration as a function of sunspot number in Figure 5. Basically, both Be-7 production rate and surface concentration decrease with an increase of the sunspot number. Dependence of the Be-7 concentration on the solar activity was proposed [12], [13] and the present result seems to support the previous proposals. The data of Be-7 concentration, however, scatter compared with the Be-7 production rate.

Here we discuss a possibility that causes the scatter of the measured Be-7 concentrations. The Be-7 concentration in surface air is not directly proportional to the Be-7 production rate because Be-7 produced in the upper atmosphere is transported to the surface by complex air mass motions. This transport process is a meteorological phenomenon and is not directly dependent on the solar activity. Seasonal variations in atmospheric motions were reported in Japan and the surface Be-7 concentrations are enhanced in spring and autumn [4], [14], [15]. The seasonal enhancements have been known to vary from year to year. The scatter of measured Be-7 concentrations is most likely to be due to the meteorological condition. In order to study the detailed variations in the surface Be-7 concentration caused by the solar activity and the air mass motions, we need more data of Be-7 concentration measured at various locations in the world.

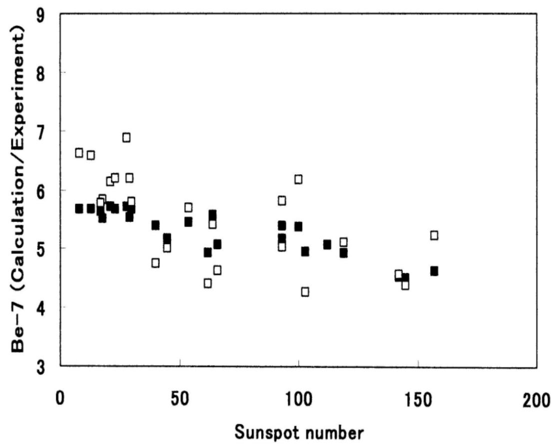

Figure 5: Variations in the ratio of simulated Be-7 production rate (solid square) and the measured Be-7 concentration (open square) in 1983-2006.

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