Production of ^{7}Be Nuclei in the Earth's Upper Atmosphere from Galactic Cosmic Rays and Solar Energetic Particles

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Abstract

Galactic cosmic rays (GCR) produce ^{7}Be radioactive nuclei from nuclear interactions with the atmospheric N and O nuclei. In addition, extraordinarily intense solar energetic particles (SEP) associated with a great coronal mass ejection (CME) event contribute to production of ^{7}Be nuclei, though a frequency of such solar proton event is very low and its duration is less than a few days. The SEP proton spectrum is so steep that most of ^{7}Be is produced in a thin top layer of the polar atmosphere. We calculate the global average ^{7}Be production rate in the upper atmosphere taking account both GCR and SEP protons. The production rate of ^{7}Be by the intense SEP event increases about a few tens times that by GCR. We compare the present calculation with the measurement of ^{7}Be and discuss the SEP effect to ^{7}Be production.

1. Introduction

^{7}Be radioactive nuclei result from GCR and SEP interactions with N and O nuclei in the atmosphere. The revised cross sections of ^{7}Be production from p + N and p + O reactions were reported by Bodemann et al. (1993). Their result shows that >20 MeV protons contribute to the ^{7}Be production. GCR protons produce a large part (70%) of ^{7}Be in the stratosphere and a small part (30%) in the troposphere (Lal and Peters, 1967). Solar activity dependence of ^{7}Be concentration on the ground level was reported (Megumi et al., 2000). In addition to GCR, highly intense solar protons arrive at the Earth in association with a large solar event. The SEP proton spectrum is soft and most of ^{7}Be is produced near a top of the atmosphere.

In this paper we calculate the production rate of ^{7}Be taking account both GCR and SEP protons and make comparison with the measurements of ^{7}Be.

2. ^{7}Be Production in the Earth's Atmosphere

The global average ^{7}Be production rate in the atmosphere is given by the following formula:

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$$Q = G \int_{Eo} F(E)\{1 - \sin\lambda(E)\}y(E)[1 - \exp\{-(R(E) - R(Eo))/\Lambda(E)\}]dE$$

Here G is the probability of escape of ^{7}Be to interplanetary space (we assume G=0.3), Eo is the threshold energy of ^{7}Be production (Eo is 10MeV), $F(E)$ is the proton energy spectrum of GCR or SEP, $1 - \sin\lambda(E)$ is the fraction of the Earth's surface which is accessible to particles of energy E, corresponding to the cutoff rigidity at geomagnetic latitude λ, $y(E)$ is the yield per nuclear interaction, $1 - \exp\{-(R(E) - R(Eo))/\Lambda(E)\}$ is the probability that a particle (interaction mean free path in air is $\Lambda(E)$ and range is $R(E)$) produces a nuclear interaction before the threshold energy by ionization loss. $R(E)$ is approximated by $2.5\text{x}10^{-3}E^{1.75}$ $g\ cm^{-2}$ in the energy range of interest. The cross sections for production of ^{7}Be from p + N and p + O reactions are shown in Fig. 1. The cross section is roughly constant (about 10 mb) above 100 MeV and independent on a target nucleus. It indicates that the average yield of ^{7}Be per nuclear interaction remains almost constant ($4.5\text{x}10^{-2}$), though the nucleon spectrum becomes harder as one approaches the top of the atmosphere.

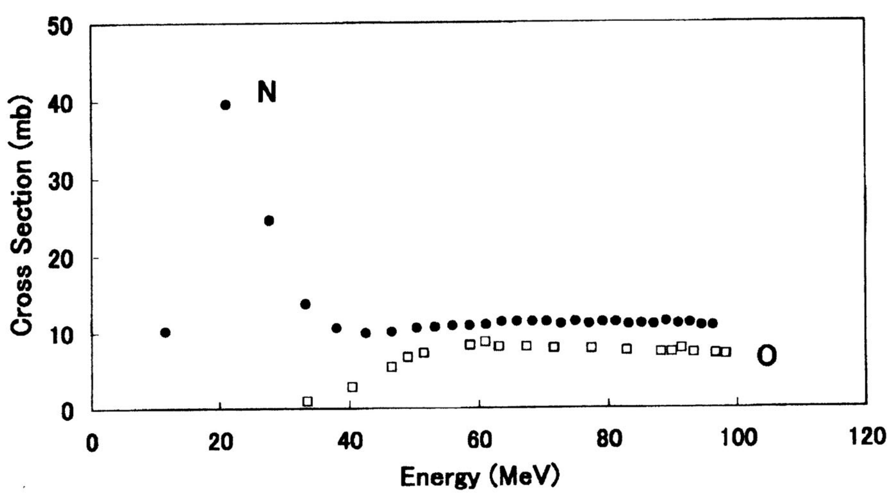

Fig. 1. Cross sections for production of ^{7}Be from p + N and p + O reactions.

The number of ^{7}Be nuclei produced by GCR per minute per gram of air at different geomagnetic latitudes (λ=60, 47, 30 and 0 degree) is plotted in Fig. 2 as a function of atmospheric depth. The typical GCR and most intense SEP proton spectra on July 14, 2000 are shown in Fig. 3. Here we assume that the vertical cutoff rigidity at geomagnetic latitude λ is P(λ) = 15 $\cos^4\lambda$ GeV/c. 15 GeV/c is the cutoff rigidity at the equator. The energy spectrum of SEP protons is so steep that low-energy protons below a few tens of MeV are dominant. Arrival of most SEP protons is essentially confined to the polar region.

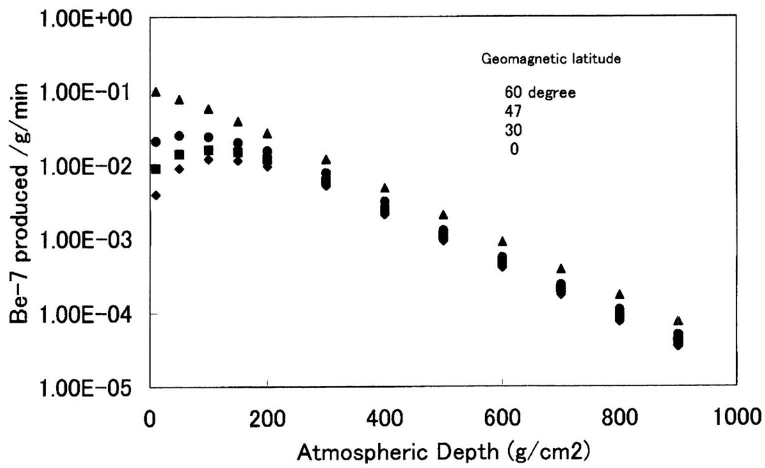

Fig. 2. The number of ^{7}Be nuclei at geomagnetic latitudes 60, 47, 30 and 0 degree produced by GCR per minute per gram of air.

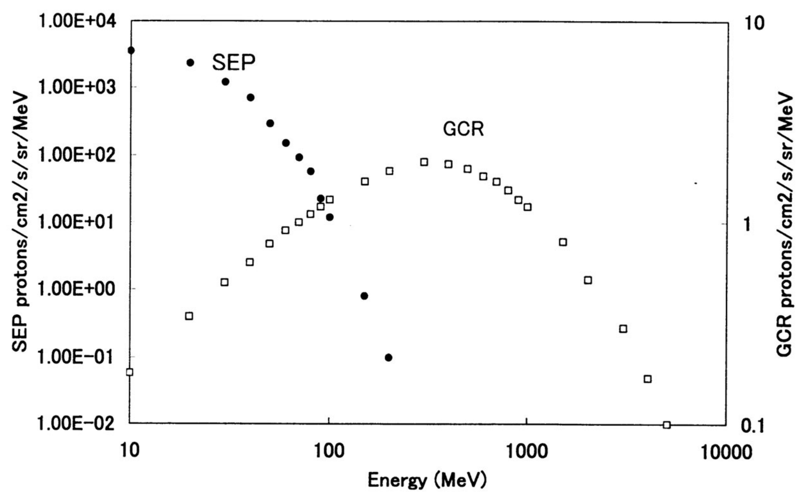

Fig. 3. GCR and SEP proton energy spectra

The proton fluence (time-integrated flux over the event duration) of the intense SEP event on July 14, 2000 amounts to 10^{10} protons cm^{-2} above 10 MeV, while the corresponding GCR proton fluence is a few times 10^{5} protons cm^{-2}. Hence, an extraordinarily high-flux of low-energy SEP protons reach the vicinity of the geomagnetic poles after the intense SEP event. The duration of SEP events is less than a few days. Since the threshold energy of ^{7}Be production is about 10 MeV, most of ^{7}Be are generated in a thin layer of the polar atmosphere. The global average production rates by GCR and SEP are estimated to be Q(GCR)

= 0.1 (0.07 in the stratosphere and 0.03 in the troposphere) and Q(SEP) = 2.4 ^{7}Be cm^{-2} s^{-1}, respectively. The calculation suggests that once a great SEP event occurs, a large number of ^{7}Be are produced in the top atmospheric layer of the polar region. In a case of the July 14, 2000 SEP event, the global production rate by SEP is a few tens times that by GCR. However, a frequency of the great solar proton event is very low even in the solar maximum period.

3. Discussion

The ^{7}Be concentration at altitudes of 9-12 km (11-60 north degree) was measured in samples from NASA's Global Atmospheric Sampling Program in 1978 to 1979 (Dutkiewicz and Husain, 1985). The average production rate of ^{7}Be in the upper troposphere at 11 km was estimated at 0.02 ^{7}Be cm^{-2} s^{-1}. This is in roughly agreement with the present calculation.

Upper atmospheric ^{7}Be nuclei were observed with the Long Duration Exposure Facility (LDEF) at altitudes above 320 km in 1986-1990 (Fishman et al., 1991; Phillips et al., 2000). The observation exhibited that the ^{7}Be concentration at the LDEF alttitude is much higher (of three orders of magnitudes) than that in the stratosphere. It suggests that there is a physical process that ^{7}Be nuclei are rapidly and effficiently transported to higher altitudes. Further, the LDEF data indicated that a correlation between the ^{7}Be concentration and the SEP flux. In particular, the high concentration of ^{7}Be was measured in association with the large solar proton event in October, 1989. The ^{7}Be concentration increased more than ten times the usual ^{7}Be level. It supports that large solar proton events contribute to the ^{7}Be production in the upper atmosphere.

There is the possibility that ^{7}Be nuclei come directly from the Sun. The ^{7}Be nuclei are produced from the α-α nuclear reaction in solar flare (Ramaty et al., 1974; Share and Murphy, 1997). In order to confirm the direct contribution of ^{7}Be from solar flares, we need to detect ^{7}Be nuclei in SEP. However, we have had no obervational evidence for ^{7}Be from the Sun.

4. References

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