Proceedings of ICRC 2001: 4124 © Copernicus Gesellschaft 2001

ICRC 2001

# The correlation between particle fluxes above 1,000 km altitude in the polar regions and those observed at the geostationary orbit

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**Abstract.** The nitrate concentration in polar ice appears to be correlated with the intensity of solar and/or galactic cosmic rays in the polar regions. Watanabe et al have found an 11-year variation of the nitrate concentration in an ice core from Antarctica, which, surprisingly, correlates positively with sunspot number. However the contribution of cosmic rays to the production of odd nitrogen in general has not yet been established.

A very good correlation has been found between the fluxes of low energy (7∼15 MeV) particles observed at altitudes of 3,000 km in the polar region by the Akebono satellite and at the geostationary orbit by the GOES satellite, 36,000 km above the equator. We have investigated the impact of cosmic rays on the atmosphere over the polar regions. A very important conclusion has been obtained in that the impact of SEP was 14 times stronger than that of GCR during the solar cycle 22.

## 1 Introduction

Recently, an interesting suggestion has been made that cosmic rays might affect the Earth's climate (Svensmark and Christensen, 1997; Svensmark, 1998). It has been known for a long time that the cosmic radiation does influence the Earth's environment. Typical examples are the concentration of $^{10}$Be in polar ice and radio carbon ($^{14}$C) in tree rings. These clearly correlate with the solar and geomagnetic modulation of cosmic rays (Raisbeck et al., 1987; Kitagawa and Matsumoto, 1995; Kocharov, 1996; Castagnoli et al., 1998; Kitagawa and Plicht, 1998; Beer, 2000). The concentration of nitrate in polar ice cores is another good example.

Zeller and Parker (1981) observed an 11-year variation of the nitrate abundance in polar ice cores. Recently, Watanabe et al. (1999) also found a periodicity of the nitrate abundance in an Antarctic ice core (Figure 1). Shea and Smart, based on Zeller's data, reported that several peaks of nitrate concentration in polar ice cores coincide in the time with well-known large solar flares (**?**). Kocharov has pointed out that some peaks correspond to major natural phenomena such as the Tunguska meteoroid impact (1908) and the Carrington white light flare (1859) (**?**).

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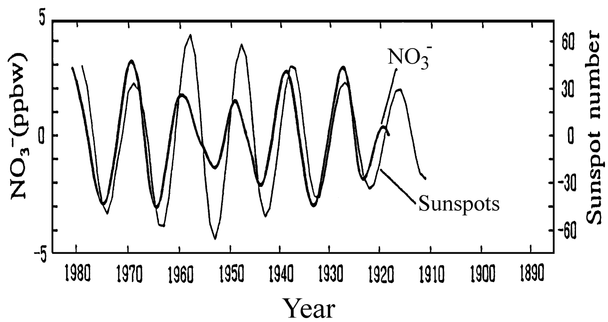


**Fig. 1.** Nitrate concentration in the Antarctic ice core and the sunspot number (coutesy of Watanabe et al, 1999).

The most well-known 11-year variation is solar activity. However it is not so clearly understood why the nitrate concentration in ice cores should correlate with solar activity, and what the corresponding mechanisms responsible for the correlation might be. We have investigated this subject from the view point that the 11-year variation of the nitrate abundance in the polar regions is produced by cosmic rays. To resolve this question, we have investigated particle flares over the polar and the equatorial regions from space, using data from three satellite, EXOS-D, GOES-6 and IMP-8.

Following a description of the method of analysis of these satellite data given in section 2, an interesting new result is reported in section 3. Finally in section 4, we present an interpretation why the 11-year periodicity in the abundance of nitrate appears in ice cores.

## 2 The data and the method of analysis

In order to understand the correlation between the variation of nitrate abundance in polar ice cores and the intensity of cosmic rays penetrating the polar atmosphere, we require a long term data set for cosmic rays in the polar regions. However, there is no satellite which has passed over the polar regions for a long period (more than one solar cycle). In this paper we examine the possibility of using the data from the geostationary satellite GOES, which has been in orbit for a long time. After giving an explanation how the energy spectrum of galactic cosmic rays and solar energetic particles is obtained from the data of the GOES satellite, we compare the result with the data obtained by the EXOS-D satellite which passed over the polar region. Quite surprisingly we found a strong correlation between the two data sets. These results are presented in this paper.

### 2.1 The data of GOES-6 on the GCR and SEP fluxes

First we introduce the GOES-6 satellite: GOES-6 was launched by NOAA (National Oceanic and Atmospheric Administration) on April 28, 1983. The satellite remained in the geostationary orbit at an altitude of 36,000 km over the equator until November 1994. The data from the GOES-6 satellite are available to the public on the World Wide Web on the NOAA homepage. The data which we used for our analysis comprises the 5-minute average values of the proton flux [counts/cm$^2$ sec sr MeV]. They were obtained by the GOES-6 satellite from 1986/1/1 to 1994/4/30. Table 1 indicates the energy range of each channel of the detectors. In the present analysis, we used the data of channels P2∼P7. For the period from Nov. 1994 until the present, the data of GOES-8 are used.

We obtain the background produced by GCR, calculating total flux of GCR year by year. Next, we derive the flux of SEP produced by solar flares. That was defined as an increase of the intensity when the intensity of the P2 channel exceeded twice the ordinary background. When such an abnormal increase continued for more than one hour, we define the event as SEP. Then we integrate the flux of each energy channel for the period and calculate the energy spectrum of SEP events for each year (Figure 2). All data within one year are combined and the one year average spectrum calculated.

### 2.2 The data of EXOS-D on the proton flux over the polar regions

The data from the EXOS-D satellite have been used in order to obtain the intensity of cosmic rays over the polar regions. The EXOS-D satellite, named "Akebono" in Japanese, was launched by ISAS (the Institute of Space and Astronautical Science) on February 22, 1989. In order to observe auroral events and phenomena related to auroras, its orbit is semi-polar with an initial apogee of 10,500 km, perigee of 272 km, inclination of 75.1°, and an orbital period of 212 min. The proton flux [counts/cm$^2$ sec sr] was obtained for the channels indicated in Table 1. The flux data were given in 16 second intervals. In the analysis, we compare the data from the P6 channel obtained by EXOS-D with the data from the P3 channel obtained by GOES-6.

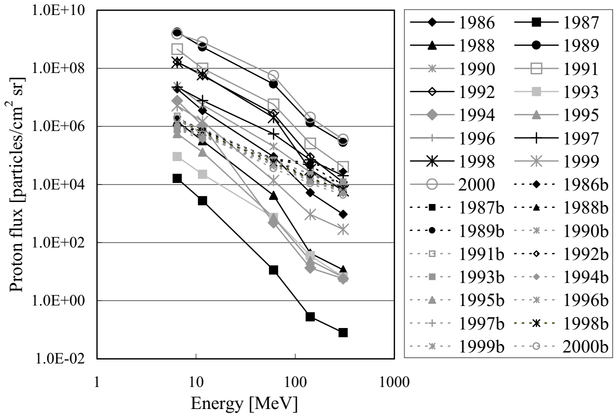


**Fig. 2.** One year proton spectrum for solar flare particles (solid line) and background (dotted line) between 1986 and 2000. The background flux does not change so much.

The EXOS-D satellite flies in the above-mentioned oval orbit between -75°and 75°geographic latitude ($\phi$). We define the proton flux over polar region as the value obtained by EXOS-D at latitudes $\phi \geq 60°$. Moreover, we have selected the data for the proton flux between 1989/10/19 and 1989/10/28. During this period, the EXOS-D satellite orbited at an altitude between 1,100 km and 6,700 km.

## 3 An interesting relation between GOES data and EXOS-D data

When a comparison was made between the data of EXOS-D and the data of GOES-6, a very interesting relationship between the two data sets was found. The intensities of cosmic ray flux obtained over the polar regions at an altitude between 1,100 km and 6,700 km and in the equatorial plane at geostationary orbit are nearly equal. The intensity of protons of SEP obtained from the EXOS-D satellite coincided quite well with the flux obtained by GOES-6 (Figure 3). This is a quite surprising result. Four other SPE data sets have been analyzed in the periods 1990/5/21∼6/2 (Figure 4), 1991/6/1

| GOES-6 satellite [counts/cm$^2$ sec sr MeV] | EXOS-D satellite [counts/cm$^2$ sec sr] |
|---|---|
| P1: 0.6∼4.2 [MeV] | P4: 30∼38 [MeV] |
| P2: 4.2∼8.7 | P5: 15∼30 |
| P3: 8.7∼14.5 | P6: 6.6∼15 |
| P4: 15∼44 | |
| P5: 39∼82 | |
| P6: 84∼200 | |
| P7: 110∼500 | |

**Table 1.** Energy ranges of the proton channels on the GOES-6 and EXOS-D satellites.

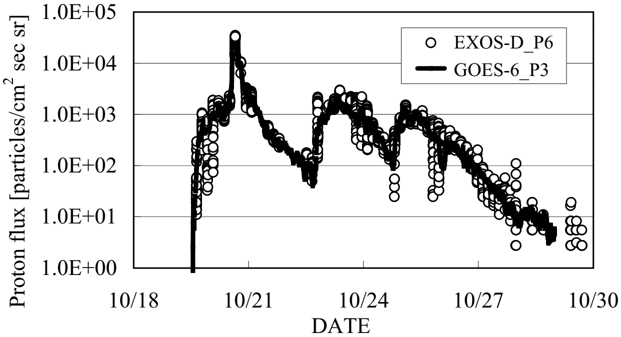


**Fig. 3.** A comparison of the data between EXOS-D and GOES-6 for the flares of Oct. 20, 1989.

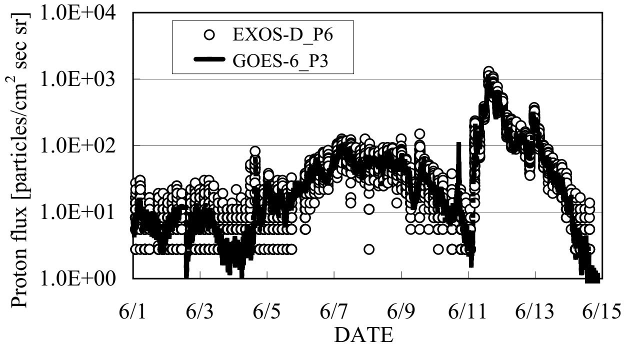


**Fig. 5.** A comparison of the data between EXOS-D and GOES-6 for the flares on June 1∼15, 1991.

∼6/14 (Figure 5), 1992/5/8∼5/15 and 1992/10/30∼11/8. As shown in Figure 4 and 5, identical results were obtained.

However, the cutoff rigidity at the orbit of GOES-6 is different from the cutoff rigidity at EXOS-D which passes over the polar regions. The cutoff rigidity where GOES-6 was located at an altitude of 36,000 km over the equator is approximately 50 MeV (**?**). Therefore, it was impossible for solar cosmic rays with energies between 7 MeV and 15 MeV to enter there directly.

The coincidence of the proton fluxes obtained by GOES-6 and EXOS-D is not by chance but presumably arises because the cut-off rigidity of cosmic rays at the GOES-6 satellite at 36,000 km over the equator is nearly the same as the cut-off rigidity of the EXOS-D orbit over 3,000 km at $\phi$=60°.

Since a good correlation has been found experimentally between two proton fluxes between the GOES-6 satellite and the EXOS-D satellite, we shall use the data of GOES-6 as a proxy for the cosmic ray intensity over the polar regions. The particles observed by the GOES satellite must somehow be transferred from outside the magnetosphere to the geostationary orbit. Here we have used a dipole model for the geomagnetic field. However even if we will use precise geomagnetic model of Smart et al. (Bütikofer et al., 1995; Smart et al., 2000), which takes account of the day and night effect, the discussion will be not essentially different. Since at the geostationary orbit, even day and night the magnetice field does not change so much. According to the measurment by the GOES satellites, it is normally (100 $\pm$ 20) nT. Here we have demonstrated that the energy spectrum of proton fluxes above the polar regions is nearly the same as over the equatorial plane at the geostationary orbit. In the next section, we will study the long term variation of cosmic rays at the polar region, based on this fact.

## 4 Discussion and Conclusion

In order to understand the possible effects of SEP or GCR which might make an 11-year variation of nitrate abundance in polar ice core, data on the proton flux obtained by GOES-6 and EXOS-D over the period 1986/1/1∼1994/4/30 were analyzed. Here an important point must be mentioned: the production rate of nitrates by cosmic rays is proportional to the total energy flux of the incoming ionizing particles. In other words, the total energy by cosmic rays relates to the production of nitrate through the ionization process. Although the ratio between SEP and GCR fluxes during the solar maximum (1989∼92) turns out to be between 1 and 86 (Figure 6), during solar minimum (1986∼88, 93∼95) the ratio becomes less than 0.1 (Figure 6). Figure 6 also shows the sum of the total loss energy of SEP and GCR for each year. The

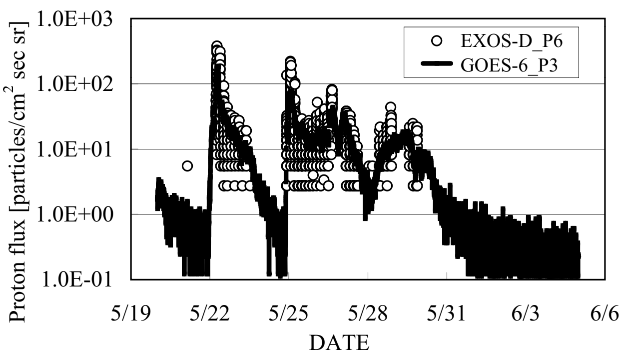


**Fig. 4.** A comparison of the data between EXOS-D and GOES-6 for the flares on May 21∼June 6, 1990.

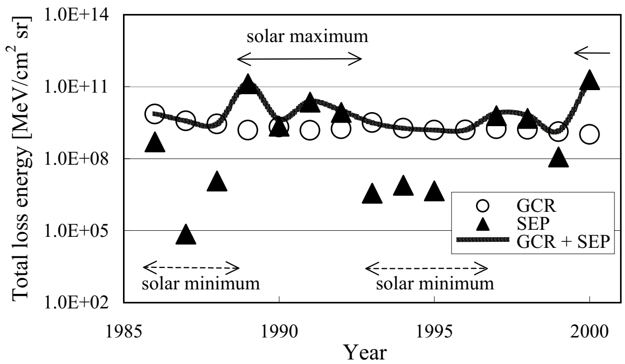


**Fig. 6.** The total loss energy of SEP and GCR in the Stratosphere for each year between 1986 and 2000. The gray line shows the total loss energy of SEP and GCR.

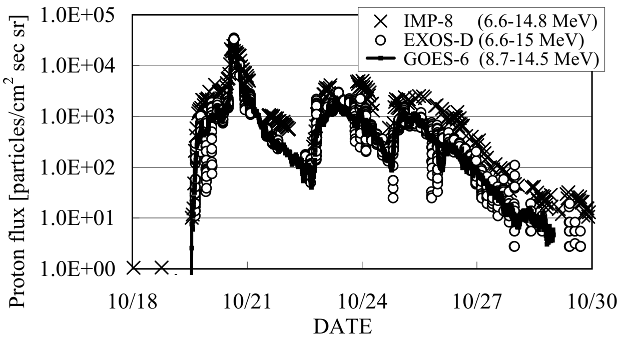


**Fig. 7.** A comparison of three data sets of the EXOS-D, GOES-6 and IMP-8 satellites for the flares of Oct. 20, 1989.

sum is denoted by the gray line. The ratio of the sum during solar maximum (1989∼92) and solar mimimum (1993∼96) is about 20.

The peaks of the 11-year variation of nitrates in the polar regions are positively correlated with solar activity. Therefore from these data, we conclude that the 11-year variation of nitrate abundance in the polar regions is produced mainly by SEP. The effect of GCR on the production of nitrate is inversely correlated with solar activity, and is less effective as a asource of nitrates than SEP.

In order to understand the transport mechanism of protons from the outside of the magnetosphere to the geostationary orbit via the polar region, we compared the GOES-6 and EXOS-D data with the IMP-8 satellite data for the flares of Oct. 20, 1989 (Figure 7). The proton fluxes detected by the three satellites flying in different positions showed similar increases at the time of large solar flares. This observation was sufficiently surprising to warrant mention in this paper, however the transport mechanism for protons entering from the polar region to the equatorial plane at the geostationary orbit must be investigated more precisely in the near future. A possible transpotation route of the protons is visualized in Figure 8.

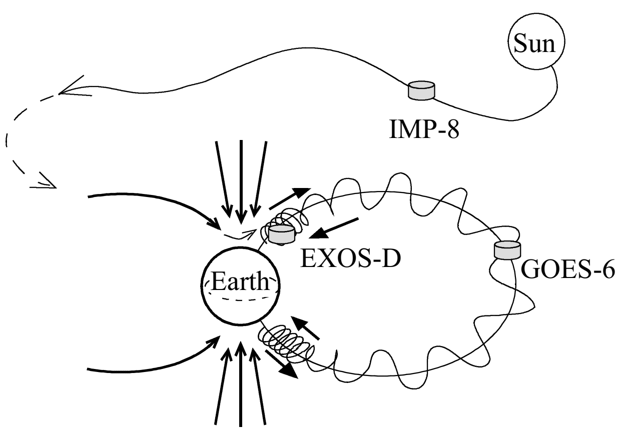


**Fig. 8.** Sketch of proton tajectory from the sun entering into the polar regions to the equatorial geostaionary satellite.

The other interesting investigation which must be made in future is an accurate calculation of the flux of SEP over the polar regions, taking account of the precise rigidity distribution for charged particles over each sub-region of the Antarctic and the Arctic. The nitric oxide is formed by cosmic rays and bacteia by the following process: $N + O_2 \rightarrow NO + O$ (by GCR) and $N_2O + O \rightarrow 2NO$ (bacteria). According to Jackman et al., the ratio should be almost 1:1 in the polar regions ($\phi > 50°$) (Jackman et al., 1980). Then from our result, much more strong effect must be observed in the antarctic ice core. The change of particle intensity between solar maximum and minimum is 20. Therefore, the variation must be recorded in the ice core should be a factor 20. However the observed increase was only 0.2. The difference between prediction and observation may result from the reason that the ice core was not sampled directly under the antarctic magnetic pole, or perhaps the incoming particles over the polar regions might stay for a while and then preticipate over the earth. The recording efficiency expected for the ice core is 1 %.

We have pointed out in this paper that the data of the GOES satellite can be used for the estimation of the relative fluxes of galactic and solar cosmic rays above the polar regions. Also the 11-year variation of the nitrate abundance at polar ice can be accounted for by the variation of SEP + GCR over polar regions. Thus the nitrates in the polar regions must be produced by chemical processes induced by cosmic ray produced ionization. This new knowledge will be useful in order to understand the global effect of cosmic rays on the Earth's environment.

*Acknowledgements.* The authors would like to thank to Prof. T. Nagai for providing us the EXOS-D satellite data. We also thank to Prof. Sir Ian Axford for reading this manuscript.

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