29th International Cosmic Ray Conference Pune (2005) **2**, 207–210

Sun's Shadow Variation During the Recent Solar Cycle 23 Observed with the Tibet Air Shower Array

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The Sun's shadow generated by multi-TeV cosmic-ray particles has been continuously observed with the Tibet-III air shower array in 2000 through 2004 during the active period of the Solar Cycle 23 except for winter seasons (Nov. - Feb.) when the Sun moves along the low elevation tracks. According to many observations of the activity, especially clear in the sunspot number, the Solar Cycle 23 has a dip called Gnevyshev Gap early in 2001. In the yearly variation of the Sun's shadow, it becomes faint with increasing solar activity and becomes deep with declining activity. We observed unexpected deepening of the Sun's shadow just in the year 2001 when Gnevyshev Gap appeared.

1. Introduction

As well known, the configuration of the solar and interplanetary magnetic fields considerably changes with phases of the solar activity cycle. The solar activity in Cycle 23 is gradually declining from high state in 2000-2002 to quiet phase during years 2002 through 2004[1]. In the period just at the solar maximum phase, the phenomena of a dip in the sunspot number profile, sometimes double ones, which is called Gnevyshev Gap (GG) were reported[2] in the respective solar active phases from 1950s to 1970s. This empirical phenomena often appear at the maximum phase in the variation of the sunspot number, and is considered to have a relation with the reversal process of the solar dipole-magnetic field[3].
The Tibet air shower array, for the first time, observed the unexpected large displacement of the Sun's shadow in the two-dimensional cosmic-ray intensity map in 10 TeV region[4], using the 1991-1992 data. We have reported that the Sun's shadow was much affected by the changing solar and interplanetary magnetic fields[5]. Around the year 2001, the solar activity was in the highest state during the solar Cycle 23. In this paper we discuss the variation of the Sun's shadow in the period covering the Cycle 23, and discuss the correlation between the Sun's shadow and the smoothed number profile of sunspots, whose local and powerful fields would disarrange the Sun's dipole-magnetic field and weaken its strength, in relation to GG seen in 2001 just at the maximum phase.

2. Behavior of the recent solar activity

A behavior of the solar activity appears remarkably as a transition of the sunspot number. As shown in Figure 1, the sunspot number(circles) meets a peak phase from the year 2000 to 2002 in the solar Cycle 23, and a dip like GG is noticed in the sunspot number around 2001.
The behavior of the Sun's shadow seen in the multi-TeV cosmic-ray intensity map is strongly affected both by the dipole-magnetic field in the solar circumference and interplanetary magnetic field (IMF). The strength of solar magnetic field at the source surface (at 2.5 solar radius) is observed by the Stanford group as the Stanford mean solar magnetic field(SMSMF)[1]. It is well understood that the IMF showing an Archimedes spiral is formed as a result of the transport of the photospheric magnetic field by the solar wind flowing continuously from the rotating Sun. The strength and direction of IMF at the Earth orbit are regularly observed by IMP-8 and ACE satellites[6][7]. Figure 1 also shows monthly variations of the strength of IMF at Earth's orbit (diamonds), and SMSMF(squares), demonstrating the correlation of the SMSMF and IMF with the solar activity which is approximately substituted by the sunspot number. This figure suggests that the amplitude of the variation of SMSMF at 2.5 solar radius is three times or more than that of IMF at the Earth's orbit. Although dips similar to GG are seen in profiles of these observed quantities as well, they are much smaller changes than that in the variation of the sunspot number.

3. Observation with the Tibet-III air shower array

The effective area of the Tibet array has been gradually enlarged, by several steps, to large and dense ones by adding the same type detectors to the preceeding Tibet-I and II(HD) arrays. The Tibet-III array, at the step of late in 1999, is consisting of 533 detectors in a lattice perturn of 7.5 m spacing with the area of 22000 m^2. Furthermore, the full-scale Tibet-III with 697 fast timing (FT) detectors covering the effective area of 36900 m^2 has been operating from November 2003. This array can detect air shower events in the energy region above a few TeV with frequency of 1.7 kHz, about 85 times of the Tibet-I array[8].
Hence, we can obtain a sufficient number of events to study the annual variations of the position of the Sun's shadow center against the apparent Sun's center on the cosmic-ray intensity map. In the analysis of the Sun's

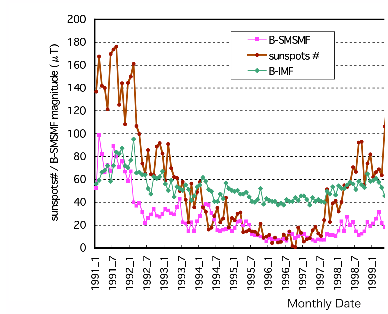

Figure 1. Variation of magnitudes of IMF at Earth's orbit by the IMP-8 and ACE satellites (diamonds), SMSMF at 2.5 solar radius (squares) and of the sunspot number (circles).

shadow we do not use the data obtained from November to February, because it results in higher the primary cosmic-ray energy for inclined showers in winter with much lesser the event frequency and also with lesser the displacement of the Sun's shadow center. So, those data are inadequate both in statistics and in energy for the purpose of this paper. Hence, the Sun's shadow analysis is available in 10 TeV region for all observation period after 1996 but available in 3 TeV region only after 1997 using Tibet-IIHD and Tibet-III array.

4. Annual variations and Correlation of the Sun's shadow with the other observations

Figure 2 shows the annual variations of the Sun's shadow in 3 TeV region around the maximum phase (2000, 2001, 2002) and in the decreasing phase (2003, 2004) in the solar Cycle 23 observed with the Tibet-III high density array with 7.5 m detector spacing. In this figure, the Sun's shadow around the maximum phase can be seen in the 2001 data, but seen in neither of the 2000 and 2002 data. It is interesting to learn from Fig. 1 that the present solar activity has double peaks at 2000 and 2002 and the year 2001 corresponds to the interval of the two peaks. Though a similar tendency appears in the 10 TeV region, the influence of GG which exerts it on the Sun's shadow remarkably in the 3 TeV region.

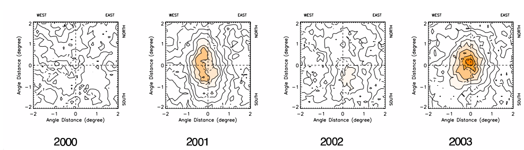

Figure 2. Annual variation of the Sun's shadow in 3 TeV region observed with the Tibet array in 2000 - 2004.

Figure 3 shows the time variations of the significances of the Sun's shadow in the 3 TeV and 10 TeV regions, and of a combined solar activity index. The combined index is composed of an average of the following three quantities: (1) the square root of the sunspot number, (2) the strength of source surface magnetic field, (3) the strength of interplanetary magnetic field (IMF) obtained by ACE satellite at 1AU. These quantities are normalized to the respective values measured at the recent solar minimum in 1996. The combined index is considered to roughly represent the magnetic field strength affecting the Sun's shadow, except for the geomagnetic field. Significance level of each Sun's shadow is calculated by the maximum likelihood method with assumed angular resolution of 1.2 degrees in a 2-dimensional Gaussian shape, respectively. Subsequently, the maximum deficit position is searched for in the area within a radius of 1.2 degrees from the apparent center of the Sun. Each significance level is normalized to the same number of events of the average biannual observation level of 2.5×10^6 events at 10 TeV and 2.0×10^7 events at 3 TeV within a circle of eight degrees from the apparent position. It seems that the normalized significance of the Sun's shadow clearly decreases in 2000 and 2002 as seen in Fig. 3. Moreover, the significance in 2001 is higher than those in 2000 and 2002. These behaviors are consistent with the GG phenomenon appeared in 2001 during the just maximum activity. It seems that an energy dependence of the variation in the Sun's shadow can be seen, too, though statistically not sufficient. We can see that there exists a clearer energy dependence of appearance of GG by comparing 3TeV and 10TeV results.

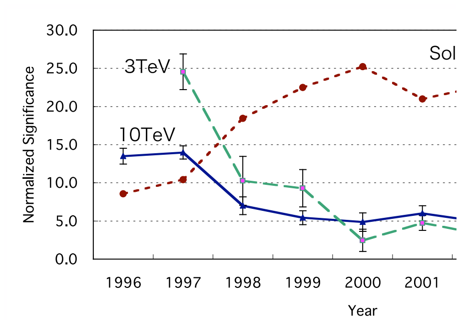

Figure 3. Correlation between the significance level of the Sun's shadow and the combined index.

5. Summary

The solar activity of the recent solar Cycle 23 is gradually declining to the quiet phase in 2003-2004 from the high state in 2000-2002. The Tibet air shower array has been continuously observing the shadow caused by shielding of galactic cosmic rays by the Sun or the Moon since 1991. We have shown that there are influences both of the solar magnetic field and of the interplanetary magnetic field on the Sun's shadow in the multi-TeV region, except for the geomagnetic field. We confirmed an effect to the Sun's shadow by the Gnevyshev Gap (GG) seen just in the maximum phase of the solar Cycle 23. Unfortunately, the bottom of the GG appeared at the off-observation period, but we found the anti-correlation between the significance of the Sun's shadow and the combined index, which represents a kind of average strength of magnetic field from the solar surface to the Earth's orbit during the maximum phase covering the GG, though the statistical significance is not so high.!

6. Acknowledgments

This work is supported in part by Grants-in-Aid for Scientific Research on Priority Areas (MEXT) and by Scientific Research (JSPS) in Japan, and by the Committee of the Natural Science Foundation and by Chinese Academy of Sciences in China.

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