"Cosmic-ray shadow" of the Sun at 3 TeV observed by the Tibet Air Shower Array

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Abstract: The Sun's shadow observed by the Tibet Air Shower Array at 3 TeV from the year 2000 to 2009 is reported. The year-to-year variations in the depth of the Sun's shadow and in the displacement of the shadow's center from the apparent direction of the Sun are discussed.

Keywords: cosmic rays, Sun, solar magnetic field

1 Introduction

The Sun, with an optical diameter of 0.5 degrees, blocks TeV cosmic rays coming from the direction of the Sun and causes a deficit in the cosmic-ray intensity, which is called the Sun's shadow. Because the Sun's shadow is influenced by the strong solar magnetic field, the continuous observation of the Sun's shadow may reveal a great deal of information on the structure and evolution of the solar magnetic field. Solar activities are connected to the properties of its strong and complex magnetic field varing with a period of ∼11 years. The solar magnetic field is carried outward by the solar wind into the heliosphere, creating the interplanetary magnetic field. The large-scale structure of the interplanetary magnetic field far from the Sun is relatively simple, whereas the coronal magnetic field close to the Sun is so complex that it has not been fully understood. The coronal magnetic field, hard to observe with instruments, has been extrapolated from measured photospheric fields. While the Potential Field Source Surface (PFSS) model [1, 2] assumes that electric currents play a negligible role in the solar corona, the Current Sheet Source Surface (CSSS) model [3, 4] takes into account large-scale horizontal currents. The CSSS model has been found to be more realistic. It can reproduce cusp structures observed in the solar corona better than the PFSS model, as well as the magnetic field strength measured near the Earth [5]. Reproducing the observed Suns' shadow by means of MC simulation would also make it possible to know which model is more realistic.

2 Experiment

The Tibet air-shower array, located at 90.522°E, 30.102°N and 4300 m above sea level, has been operating successfully since 1990. The Tibet III array, consisting of 533 scintillation counters of 0.5 m^2 each, was completed in November 1999 after several expansions [6][7]. The counters are equipped with fast-timing (FT) photomultiplier tubes and placed on a 7.5 m square grid within an area of 22,050 m^2 [8]. A 0.5 cm thick lead plate is put on top of each counter to improve fast-timing signals by converting gamma rays into electron-positron pairs. Event trigger signals are issued on condition of any fourfold coincidence taking place in the FT counters which record more than 0.6 particles. The trigger rate is approximately 680 Hz, and the energy threshold is a few TeV. The energy of primary CR particles is estimated by $\sum \rho_{\mathrm{FT}}$: the sum of the number of particles/m^2 for each FT counter. To keep data consistency, the 22,050 m^2 Tibet air-shower array is used for analysis in this paper. The angular resolution (defined as the angular radius that contains 50% of signal air-shower events produced by primary cosmic rays coming from an identical direction) and the modal energy of the array are 0.9° and 3 TeV, respectively. At present, the Tibet air-shower array has 789 scintillation counters and its effective area of 36,900 m^2.

3 Data Analysis

We use our standard event selection criteria: (1) $\sum \rho_{\mathrm{FT}} > 10$, (2) each air shower event should fire four or more FT counters that record 1.25 or more particles, and (3) eight out of the nine hottest FT counters should be contained in the fiducial area of the air-shower array. The modal energy of the cosmic rays left for analysis is estimated to be 3 TeV. The Sun's shadow (i.e. the deficit in the cosmic-ray flux caused by the Sun) is calculated as follows. The number of on-source events (N_{on}) is the number of events coming from within a 0.9° radius window centered at a given point on the celestial sphere. The number of off-source or background events (N_{off}) is the number of events averaged over eight 0.9° radius windows located at the zenith angle equal to that of the source direction, but apart in the azimuthal direction by ±6.4°, ±9.6°, ±12.8° and ±16.0°. The N_{on} and N_{off} are calculated at each point on the 0.1° grid of the Geocentric Solar Ecliptic (GSE) longitude and latitude around the optical center of the Sun. Then for each point on the grid the flux deficit relative to the number of background events $D_{obs} = (N_{on} - N_{off})/N_{off}$ is obtained.

4 Results and Discussion

Figure 1 shows the year-to-year variation of the observed flux deficit (D_{obs}) in the GSE coordinate system. Note that the fluctuation is large in 2006 because of insufficient statistics. It can be seen that the deficit becomes deeper around 2008 when the solar activity was close to its minimum in comparison to that around 2000 when the solar activity was high. One can also see that the center of the deficit seems to be displaced slightly westward from the Sun's apparant center. Figure 2 shows the yearly variation of the central deficit D_{obs} obtained by integrating N_{on} and N_{off} over the 0.9° radius window at the center of each two-dimensional map. This figure quantitatively illustrates that the depth of the deficit has a clear anti-correlation with the solar activity, and that it reaches the depth expected from the Sun's apparent size at the minimum of the solar activity (−4.3%).
The east-west displacement of the center of the deficit according to the Sun's apparent center is calculated as follows. As shown in Figure 3, the one-dimensional distribution of D_{obs} is created year by year by integrating N_{on} and N_{off} from −0.9° to +0.9° in the GSE latitude direction. We then fit the distribution with a Gaussian, and find to what extent the peak of the Gaussian is displaced according to the Sun's apparent center (e.g. $-0.26° \pm 0.04°$ westward in 2007). In 2000 when the Sun's magnetic field is strong and complicated, the deficit almost disappears and the displacement of the center of the deficit cannot be determined (see Figure 3(a)). Figure 4 shows the year-to-year variation of the east-west displacement of the center of the deficit, with regard to cosmic rays with the modal energy of 10 TeV (a) and 3 TeV (b), respectively. Let us note that, for the purpose of data consistency from 1996 through 2009, the configuration of the air shower array used for 10 TeV analysis consists of 221 FT counters which started operating in 1995 [9]. One can see in Figure 4(a) that the displacement of the deficit is nearly zero at the solar activity minimum around 1996, and that it is displaced slightly ($\sim 0.2°$) westward at the last minimum around 2009. This tendency of the displacement can be explained as follows. It is known that the stable Earth's geomagnetic field always shifts the deficit westward by $\sim 0.1°$. At the 1996 solar minimum, the polarity of the solar magnetic field was oppsite to that of the geomagnetic field, so that the solar magnetic field worked on the deficit's position in the other way and cancelled out the westward displacement caused by the geomagnetic field. On the other hand, at the 2009 solar minimum after the solar magnetic field had reversed its polarity, both the Sun's and the Earth's magnetic fields pushed the deficit westward and caused the $\sim 0.2°$ westward displacement of the deficit's center. The displacement measured at the modal energy of 3 TeV, shown in Figure 4(b), is also consistent with the tendency of shifting slightly westward as time goes, although the data before 2000 is lacking.

MC simulation using the CSSS/PFSS model is underway, in order to study which model better reproduces the observed year-to-year variations in the depth of the Sun's shadow and in the displacement of the shadow's center from the apparent direction of the Sun.

5 Conclusions

Using the Tibet air-shower array, we observed the Sun's shadow from 2000 to 2009 at the modal energy of 3 TeV. We found that the depth of the shadow has a clear anti-correlation with the solar activity, and that it reaches the depth expected from the Sun's apparent size at the minimum of the solar activity around 2009. In addition, we found that the displacement of the deficit measured at the

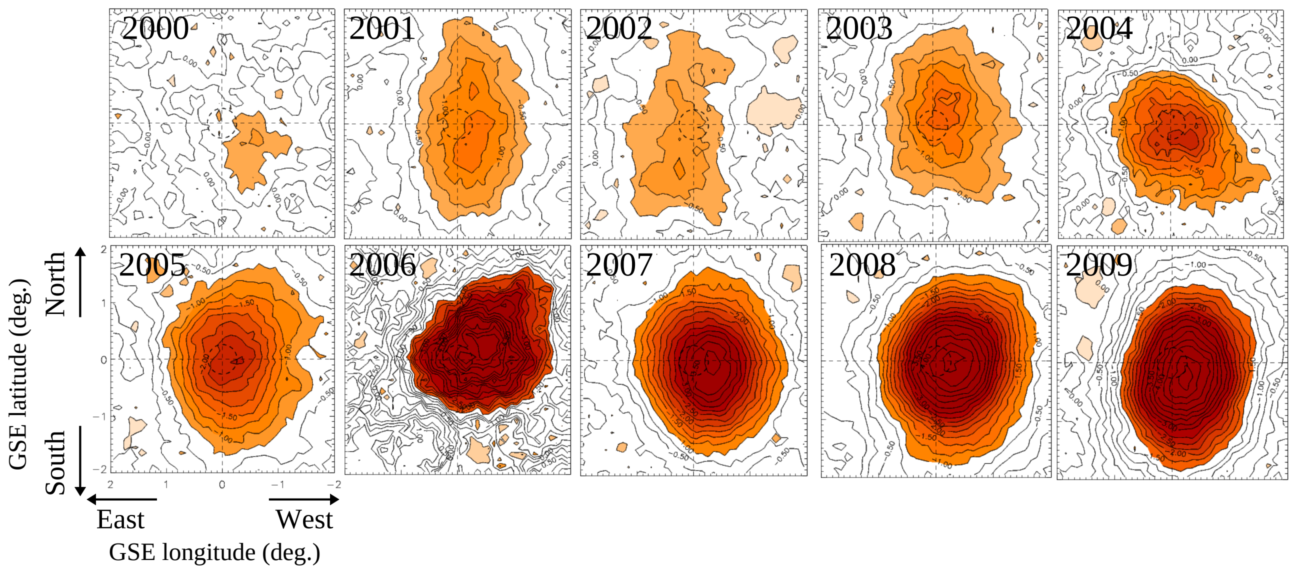

Fig. 1: Year-to-year variation of the Sun's shadow observed at the modal energy of 3 TeV from 2000 to 2009. Each panel shows the two-dimensional contour map of the cosmic-ray flux deficit in the GSE coordinate system.

modal energy of 10 TeV has the tendency of moving slightly westward from 1998 to 2009. This is consistent with the tendency of the displacement of the deficit measured at 3 TeV.

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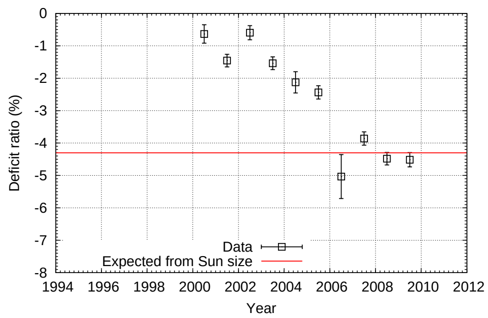

Fig. 2: Year-to-year variation of the observed central deficit measured at the modal energy of 3 TeV. The open squares represent the experimental data, and the horizontal line the deficit expected from the apparent Sun's size (−4.3%).

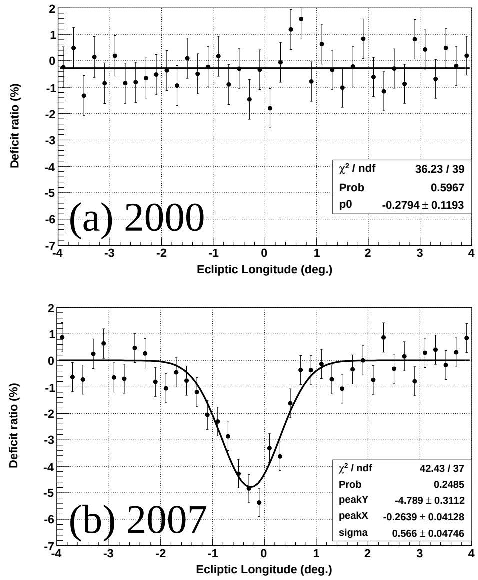

Fig. 3: One-dimensional distribution of the deficit D_{obs} in 2000 (a) and 2007 (b) measured at the modal energy of 3 TeV, obtained by integrating the deficit from $-0.9°$ to $+0.9°$ in the GSE latitude direction. The solid lines in (a) and (b) are a constant fit and a Gaussian fit to the data, respecitively.

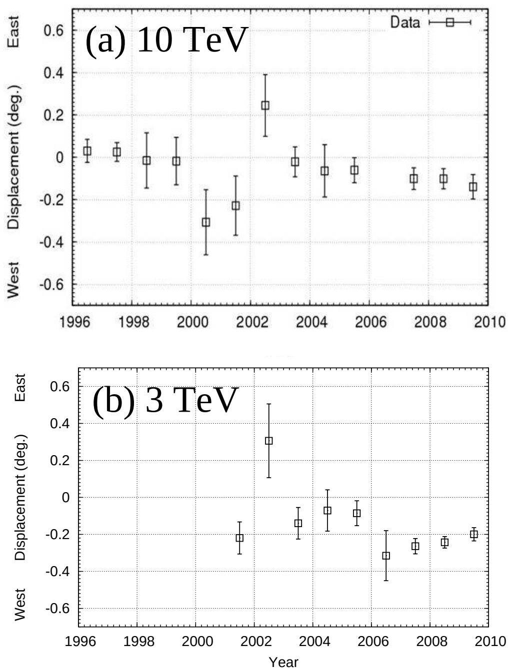

Fig. 4: Year-to-year variation of the east-west displacement of the deficit's center, measured at the modal energy of 10 TeV (a) and 3 TeV (b), respectively.