



Correlation between Solar Activity and the Sun's Shadow Observed by the Tibet Air Shower Array

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Abstract: We analyze the solar cycle variation of the Sun's shadow in 10 TeV cosmic ray intensity observed with the Tibet air shower array over an entire period of the Solar Cycle 23 between 1996 and 2008. The amplitude of the variation is as large as one half of the deficit intensity expected when all cosmic rays arriving from the direction of the optical Sun disk are excluded from the observation. The correlations between the deficit intensity in the Sun's shadow and cosmic-ray modulation parameters are overall significant. Among those parameters, we find the highest correlation with the Heliospheric Current Sheet tilt-angle.

Keywords: Tibet, cosmic rays, solar magnetic field, solar modulation, Sun's shadow

1 Introduction

Since Clark [1] suggested the possibility of observing the Sun's magnetic field by detecting the "shadow" cast by the Sun in the air shower (AS) flux, the first experimental signature of the deficit flux due to the shadowing by the Sun and Moon was reported by Alexandreas *et al.* [2]. The Tibet AS experiment confirmed shadows in the multi-TeV cosmic ray intensity with a high statistical accuracy [3]. The Moon's shadow is observed stable with its center shifted westward from the optical Moon center due to the deflection of the galactic cosmic ray (GCR) orbits in the geomagnetic field [4]. On the other hand, the Sun's shadow is found varying in a correlation with the solar activity in a sense that the shadow is clear (faint) during the solar activity minimum (maximum) period [5]. It has been suggested that the Sun's shadow varies reflecting the solar cycle variation of the solar magnetic field. The precise measurement of the Sun's shadow is of particular importance because it reflects the large-scale magnetic field structure of the Sun which is one of the most difficult information to derive from other in-situ and/or remote observations.

2 The Tibet air shower experiment

The Tibet AS array has been successfully operated at Yangbajing (90.522°E, 30.102°N; 4300 m above sea level) in Tibet, China since 1990. The effective area of the Tibet AS array has been gradually enlarged, in several steps, to larger and denser ones by adding the same-type 0.5 m² plastic scintillation detectors to the preceding Tibet-I, II and III arrays. The Tibet-II array consists of 221 detectors with a 15-m span covering 36900 m² has then started operation in October 1995 [6]. The current Tibet-III was upgraded to a dense array with 7.5-m span in 1999 and 2003 [4, 7]. The AS trigger rate is ~ 230 Hz and ~ 1700 Hz for the Tibet-II and III arrays, respectively. In this paper, we keep the form of the data same throughout the observation period from 1996 to 2008 by reconstructing AS data obtained from the detector configuration of the Tibet-II array even for the Tibet-III array. We analyze AS events by the detector configuration of the Tibet-II array completed in 1995 and the event selection based on the following criteria: (1) each AS event should fire four or more detectors recording 1.25 or more particles, (2) the AS core position should be located in the array and (3) the zenith angle of the AS event should be less than 40°. After this data selection and some quality cuts, the overall angular resolution and the modal energy of the Tibet-II array is estimated to be 0.9° and 10 TeV, respectively.

3 Analysis of the Sun's shadow

In order to analyze the Sun's shadow, an on-source event number (N_{on}) is defined as the number of events arriving from the direction within a circle of 0.9° radius centered at

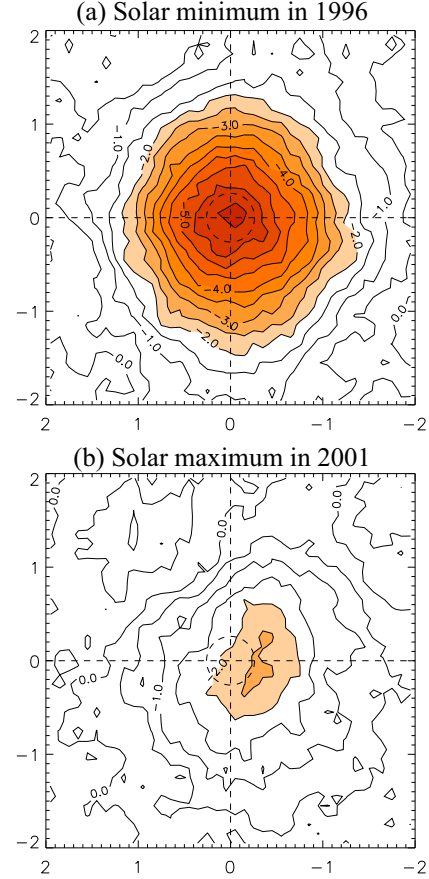


Figure 1: Two dimensional maps of the observed Sun's shadow (a) in the solar minimum (1996), and (b) in the solar maximum (2001) at 10 TeV. Each panel displays a counter map of the observed deficit intensity (D_{obs} defined in equation (1) in text) in the Sun's shadow in each year as a function of the GSE longitude and latitude.

an assumed source direction on the celestial sphere. The background or off-source event number (N_{off}) is then calculated by averaging over the number of events from the eight off-source windows which are located at the same zenith angle as the source direction but apart by $\pm 6.4^\circ$, $\pm 9.6^\circ$, $\pm 12.8^\circ$ and $\pm 16.0^\circ$ in the azimuth angle. The window radius of 0.9° is adopted for calculating each of N_{on} and N_{off} , because it is optimal maximizing the S/N ratio and sufficiently covering the entire Sun's shadow even if the observed displacement of the shadow from the optical Sun's center is taken into account. We calculate N_{on} and N_{off} on 0.05° grids of the right ascension and declination surrounding the optical Sun's center. We then derive at every grid the deficit intensity (D_{obs}) relative to the background event number defined as

$$D_{obs} = (N_{on} - N_{off})/N_{off} \quad (1)$$

by using the yearly mean N_{on} and N_{off} . Fig. 1 shows the two dimensional (2D) maps of D_{obs} in % for year 1996 (a)

and 2001 (b). In each panel of this figure, D_{obs} is plotted as a function of the Geocentric Solar Ecliptic (GSE) longitude and latitude on the horizontal and vertical axes, respectively.

4 Correlations between the Sun's shadow and the modulation parameters

Fig. 2(c) shows the temporal variation of \bar{D}_{obs} , which is the yearly average of D_{obs} within a on-source window centered at the optical Sun's center, i.e. the origin of 2D maps in Figure 1. It is seen in this panel that the average deficit intensity due to the Sun's shadow shows a clear solar cycle variation with an amplitude as large as 50% of the deficit intensity expected when all cosmic rays from the direction of the optical Sun disk are excluded from the observation as shown by solid line. Also shown in Fig. 2(a) and (b) are the temporal variation of the sunspot number and the HCS tilt-angle, respectively. The correlation coefficients between \bar{D}_{obs} and the cosmic-ray modulation parameters, are summarized in Table 1. The modulation parameters used for the correlation analyses are the sunspot number in Fig. 2(a) [8], the HCS tilt-angles in Fig. 2(b) [9], the count rate of neutron monitor (NM) [10], the IMF magnitude at the earth's orbit in nT [11] and the Stanford mean solar magnetic field in μ T [12]. While all correlations seem to be significant with the correlation coefficient exceeding 0.65, we find the highest correlation ($\gamma = +0.94$) with the HCS tilt-angle in Fig. 2(b). These correlations are also fitted by a linear function ($y = ax + b$). The χ^2 values in Table 1 indicate that the HSC tilt-angle is the best fit parameter to the linear function.

Table 1: Correlation of the observed Sun's shadow with each of the modulation parameters

Parameters	Correlation Coefficient γ	$\chi^2/d.o.f.$ $y = ax + b$
Sunspot number	0.84	49 / 11
HCS tilt-angle	0.94	14 / 11
Count rate of NM	-0.74	72 / 11
IMF near the Earth	0.74	76 / 11
Mean solar MF	0.65	92 / 11

5 Summary

The Sun's shadow observed by the Tibet AS array in the Solar Cycle 23 shows a clear solar cycle variation in a sense that the shadow is clear (faint) during the solar activity minimum (maximum) period. The amplitude of the variation is as large as 50% of the deficit intensity expected when all cosmic rays from the direction of the optical Sun disk are excluded from the observation. Among the solar cycle variations of GCR modulation parameters, we find the highest

correlation ($\gamma = +0.94$) between the Sun's shadow and the HCS tilt-angle.

The solar activity is presently going toward the solar maximum expected in 2013. The observation of the Sun's shadow in next solar cycle is very important to see the solar modulation change in the solar activity and magnetic-cycles. We develop the MC simulation of the Sun's shadow assuming a detailed magnetic field model between the Sun and the Earth effectively reproduces experimental Sun's shadow. Comparing such MC simulation with the observed Sun's shadow by the future Tibet air shower array equipped with better angular resolution, we will be capable for investigating the large-scale structure of the solar magnetic field changing in the solar activity- and magnetic-cycles.

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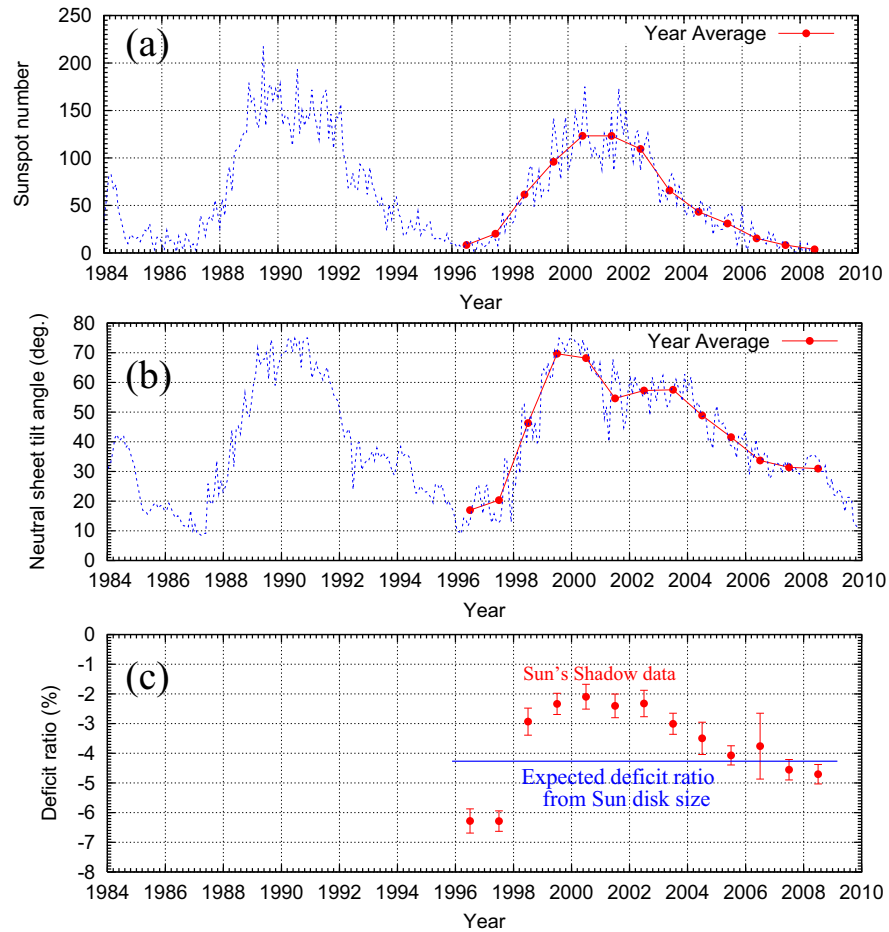


Figure 2: Solar cycle variations of the GCR modulation parameters and the Sun's shadow at 10 TeV. The solid circles in each panel from the top displays the yearly mean value of (a) the sunspot number [8], (b) the HCS tilt-angle in degree [9] and (c) yearly mean deficit intensity observed in the Sun's shadow (\bar{D}_{obs}). Solid line in panel (c) indicate the expected deficit ratio when all cosmic rays from the direction of the optical Sun disk are excluded from the observation.