

# Sun's Shadow in changing phase from the Solar Cycle 23 to 24 Observed with the Tibet Air Sower Array

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**Abstract.** The solar activity is gradually changing from the Solar Cycle 23 to 24. Sun's shadow generated by multi-TeV cosmic-ray particles has been continuously observed with the Tibet-II and Tibet-III air shower array in 1996 through 2008. We have shown that the Sun's shadow is strongly affected by the solar and interplanetary magnetic fields changing

with the solar activity in the previous papers. In this paper, we present yearly variation of the Sun's shadow in the changing phase to the Solar Cycle 24. Additionally, we discuss comparison between our observation and simulation of the Sun's shadow.

**Keywords:** Sun's Shadow, Tibet Air Sower Array, Solar Cycle 24

## I. INTRODUCTION

The Tibet air shower array for the first time observed the displacement of Sun's shadow above 10 TeV cosmic ray flux obtained by a two-dimensional analysis method [1], using the 1991-1992 data. We have shown that the Sun's shadow is strongly affected by the solar and interplanetary magnetic fields changing with the solar activity [2], [3]. Furthermore, we have reported the result on the variation of the Sun's shadow in association with the Gnevyshev gap (GG)[4], [5] appearing in the maximum phase around 2001 of Solar Cycle 23. Solar Cycle 23 is gradually declining from peak state to minimum phase around 2008 and shifting to the cycle 24.

It is known that the interplanetary magnetic field (IMF) is formed as a result of the transport of the photospheric magnetic field (PMF) by the solar wind flowing continuously from the Sun (Parker 1963). The position and density of the Sun's shadow produced in charged cosmic-rays are affected by each magnetic field of PMF, coronal magnetic field (CMF) and IMF. It is impossible to measure the CMF by a direct measurement by ground-based observation. Therefore various methods have been developed to extrapolate the PMF for the construction of the three-dimensional structure of CMF. Hakamada [6] developed a simple method to compute spherical harmonic coefficients for the potential model of the CMF from a direct observation data of PMF.

In a previous paper[7], we use this Radial Field model (RF-model) to compute CMF within 1.0 to 2.5 solar radii. In this model, CMF has only radial component at Source Surface (2.5 solar radii). Therefore, the Parker Spiral field model of IMF is smoothly connected to the RF-model at Source Surface. The simulation at the solar minimum and maximum is in good agreement with our observation.

In this paper, we show updated experimental results (but preliminary) and discuss comparison between the Sun's shadow at the previous solar minimum data with that at the recent solar minimum.

## II. BEHAVIOR OF THE RECENT SOLAR ACTIVITY

Behavior of the solar activity appears remarkable as a transition of the sunspot numbers[8]. 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 numbers around 2001. Solar Geophysical Data(SGD)[9] reports that the consensus solar minimum between Cycle 22 and Cycle 23 locate at Oct 1996. The SGD recently reports that the preliminary solar minimum between Cycle 23 and Cycle 24 was located at Aug 2008.

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)[10]. 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[11], [12]. 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 numbers. This figure suggests that the amplitude of the variation of SMSMF at 2.5 solar radius be three times or more than that of IMF at the Earth's orbit. Although dips as like as 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.

## III. OBSERVATION WITH THE TIBET AIR SHOWER ARRAY

The effective area of the Tibet array has been gradually enlarged, by several steps, to larger and higher-density ones by adding the same-type plastic scintillation detectors to the preceding Tibet-I and II(HD) arrays. The Tibet-III array, as of late in 1999, is consisting of 533 detectors in a lattice pattern of 7.5 m spacing with the area of 22000 m<sup>2</sup>. Furthermore, the full-scale Tibet-III with 761 fast timing (FT) detectors covering the effective area of 36900 m<sup>2</sup> has been operating since November 2003. This array detects air shower events in the energy region above a few TeV with frequency of 1.7 kHz, about 85 times higher than the Tibet-I array[13].

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 shadow we do not use the data obtained from September to February, because they correspond to higher primary cosmic-ray energy due to inclined showers in winter with much less event frequency and also with less displacement of the Sun's shadow center. So, those data are inadequate both in statistics and in energy for the purpose of this paper. The Sun's shadow analysis is possible above 10 TeV region (in this paper, above 10 TeV means the estimated mode energy is 10 TeV of the observed cosmic-ray distribution) for all observation period after 1996. In this paper, above 10 TeV data using 15m grid spacing sub-array is used for the Sun's shadow analysis.

## IV. OBSERVATIONAL RESULTS

Figure 2 shows the annual variations of significance of the Sun's shadow above 10 TeV observed with the Tibet-II and Tibet-III pixel skipping array with 15 m detector spacing (Note: 2006-2008 data are preliminary). The variation is remarkable in each group around the

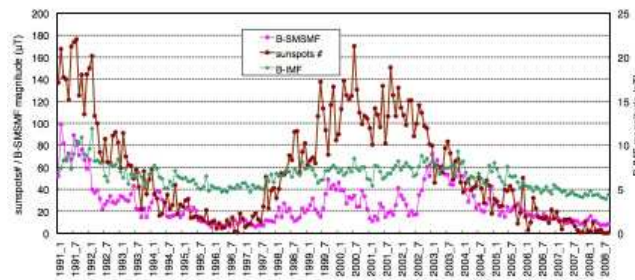


Fig. 1: Variation of magnitudes of IMF at Earth's orbit by the IMP-8 and ACE satellites (diamonds), SMSMF at 2.5 solar radius (squares) and of the sunspot numbers (circles).

previous minimum phase (1996, 1997), increasing phase (1998, 1999) maximum phase (2000, 2001, 2002), decreasing phase (2003, 2005) in Solar Cycle 23 and the latest minimum phase (2007, 2008). Unfortunately by the system trouble, annual background cosmic-ray air shower data is not homogeneous especially in 2004 and 2006. So, direct comparison is does not make sense among the annual maps in the shadow's significance level.

#### A. Background Normalization

The significance map (Figure 2) depends on the background data density. Data loss in air shower event by system troubles have a serious impact on significance maps. Figure 3 shows yearly number of background events and scatter plots of elevation angle of the Sun's shadow (on-source) events. This figure shows that serious event losses occurred in 2004 and 2006.

Therefore, we present Percentage(%) of Excess(deficit) / Background maps as the background normalized Sun's shadow. Figure 4 shows annual variation of the background normalized Sun's shadow above 10 TeV observed with the Tibet array in 1996 - 2008 (preliminary in 2006-2008). Though each map in Figure 4 can be compared with one another, one should pay an attention, because the magnitudes of statistical errors are different, especially in 2004 and 2006 data. A smooth transition is observed in this figure.

#### B. Positions of the Sun's shadow

Here, we discuss difference between the previous and latest solar minimum data. In a previous paper[14], we report that energy dependence of the displacement of the Moon's shadow in the east-west direction. The Sun's shadow or Moon's shadow in cosmic rays above 10 TeV shifted to the westward by  $\sim 0.1$  degrees due to the geomagnetic field effect[15]. Meanwhile at the previous solar minimum (1996, 1997), the Sun's shadow was located just on the apparent Sun's position. This phenomenon means that the solar and interplanetary magnetic fields negate the geomagnetic effect.

At the latest solar minimum (2007, 2008), the Sun's shadow center shifted by about 0.16 degree to the westward. This phenomenon may be explained by the solar magnetic field reversal. Unfortunately, the latest

solar minimum data are preliminary, and detailed energy dependence analysis is under way.

#### V. CONCLUSION

We report the annual variation of the Sun's shadow from Solar Cycle 23 to the changing phase to the Solar Cycle 24. We show the difference between the previous minimum phase (1996, 1997) and latest minimum phase (2007, 2008). The energy dependence analysis using the High Density Array and simulation study are needed for detailed interpretation.

#### VI. ACKNOWLEDGMENTS

The collaborative experiment of the Tibet Air Shower Arrays has been performed under the auspices of the Ministry of Science and Technology of China and the Ministry of Foreign Affairs of Japan. This work was supported in part by a Grant-in-Aid for Scientific Research on Priority Areas from the Ministry of Education, Culture, Sports, Science and Technology, by Grants-in-Aid for Science Research from the Japan Society for the Promotion of Science in Japan, and by the Grants from the National Natural Science Foundation of China and the Chinese Academy of Sciences.

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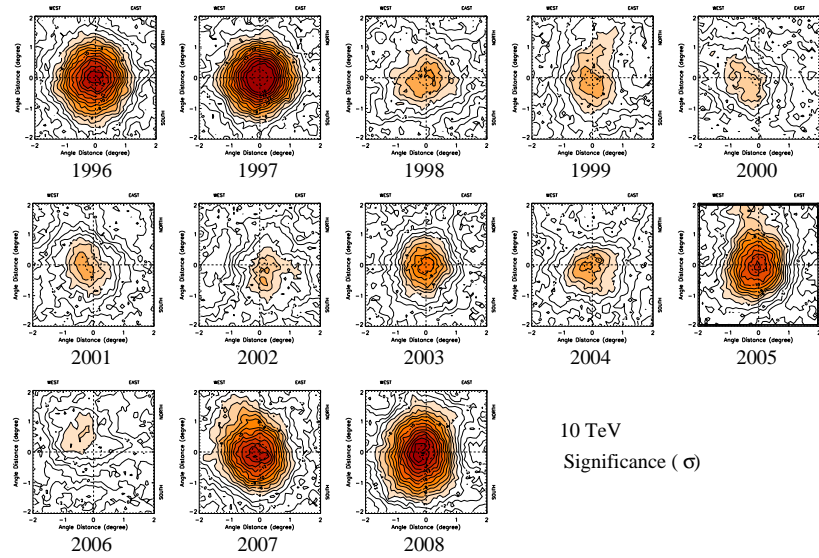


Fig. 2: Annual variation of the Sun's shadow above 10 TeV observed with the Tibet array in 1996 - 2008( Preliminary 2006-2008). Significance maps.

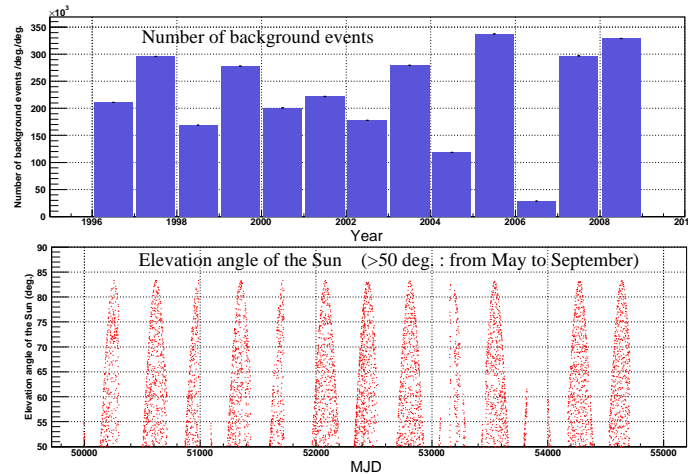


Fig. 3: Annual variation of number of background events and scatter plots of elevation angle of the Sun's shadow (on-source) events.

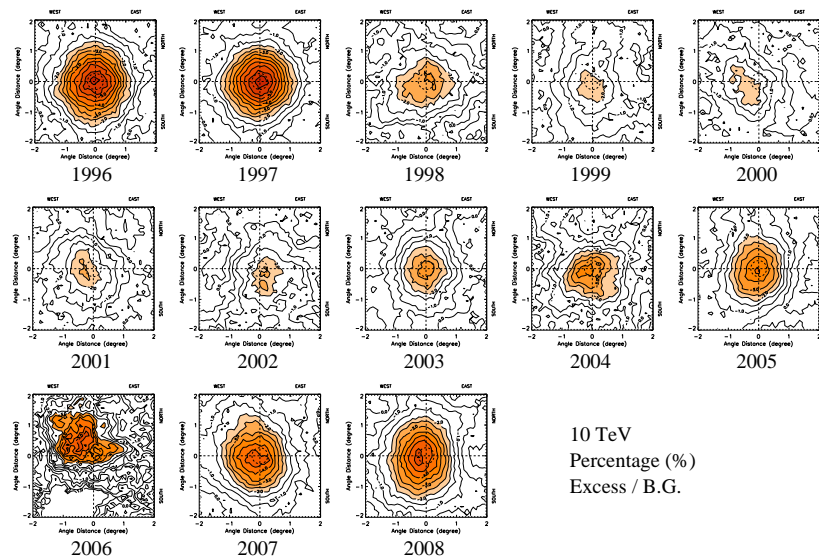


Fig. 4: Annual variation of the background normalized Sun's shadow above 10 TeV observed with the Tibet array in 1996 - 2008 (preliminary in 2006-2008). Percentage Excess / B.G. maps.