ICRC 2001

Sun's shadow in a high state of solar activity detected with the Tibet air shower array

The Tibet ASγ Collaboration

M. Amenomori[1], S. Ayabe[2], S.W. Cui[3], L.K. Ding[3], X.Y. Ding[4], C.F. Feng[5], Z.Y. Feng[6], Y. Fu[5], X.Y. Gao[7], Q.X. Geng[7], H.W. Guo[4], M. He[5], K. Hibino[8], N. Hotta[9], J. Huang[9], Q. Huang[6], A.X. Huo[3], K. Izu[10], H.Y. Jia[6], F. Kajino[11], K. Kasahara[12], Y. Katayose[13], K. Kawata[11], Labaciren[4], G.M. Le[14], J.Y. Li[5], H. Lu[3], S.L. Lu[3], G.X. Luo[3], X.R. Meng[4], K. Mizutani[2], J. Mu[7], H. Nanjo[1], M. Nishizawa[15], M. Ohnishi[10], I. Ohta[9], T. Ouchi[10], S. Ozawa[9], J.R. Ren[3], T. Saito[16], M. Sakata[11], T. Sasaki[8], M. Shibata[13], A. Shiomi[10], T. Shirai[8], H. Sugimoto[17], K. Taira[17], M. Takita[10], Y.H. Tan[3], N. Tateyama[8], S. Torii[8], H. Tsuchiya[10], S. Udo[2], T. Utsugi[2], C.R. Wang[5], H. Wang[3], X. Wang[5], X.W. Xu[3,10], L. Xue[5], X.C. Yang[7], Y. Yamamoto[11], Z.H. Ye[14], G.C. Yu[6], A.F. Yuan[4], T. Yuda[18], H.M. Zhang[3], J.L. Zhang[3], N.J. Zhang[5], X.Y. Zhang[5], Zhaxiciren[4], and Zhaxisangzhu[4]

[1]Department of Physics, Hirosaki University, Hirosaki, Japan
[2]Department of Physics, Saitama University, Saitama, Japan
[3]Laboratory of Cosmic Ray and High Energy Astrophysics, Institute of High Energy Physics, CAS, Beijing, China
[4]Department of Mathematics and Physics, Tibet University, Lhasa, China
[5]Department of Physics, Shangdong University, Jinan, China
[6]Institute of Modern Physics, South West Jiaotong University, Chengdu, China
[7]Department of Physics, Yunnan University, Kunming, China
[8]Faculty of Engineering, Kanagawa University, Yokohama, Japan
[9]Faculty of Education, Utsunomiya University, Utsunomiya, Japan
[10]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan
[11]Department of Physics, Konan University, Kobe, Japan
[12]Faculty of Systems Engineering, Shibaura Institute of Technology, Saitama, Japan
[13]Department of Physics, Yokohama National University, Yokohama, Japan
[14]Center of Space Science and Application Research, CAS, Beijing, China
[15]National Institute for Informatics, Tokyo, Japan
[16]Tokyo Metropolitan College of Aeronautical Engineering, Tokyo, Japan
[17]Shonan Institute of Technology, Fujisawa, Japan
[18]Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya Japan

Abstract. A yearly variation of the Sun's shadow was examined in the period from 1990 to 2001 using the data obtained with the Tibet air-shower array. In the quiet phase between 1996 and 1997, the Sun's shadow was observed just at the apparent position of the Sun with a high significance level, while in the active phase from 1998 to 2001, the shadow became complicated and gradually disappeared year by year. The Sun's shadow is very sharp in the quiet phase, but the form of a shadow is not clear anymore in the low energy region. We present a preliminary result on the Sun' shadow observed in 2000 - 2001 and compare it with the past data.

1 Introduction

Shadowing of cosmic rays by the Moon and the Sun was first observed with air shower arrays in 1991 (Alexandreas et al., 1991)(Fick et al., 1991). In 1993, the Tibet air-shower array observed for the first time the effect of the solar and interplanetary magnetic fields on the Sun's shadow and also of the geomagnetic field on the Moon's shadow in the 10-TeV energy region (Amenomori et al., 1993a).

The Tibet air-shower array has been gradually enlarged and condensed to increase the sensitivity for detecting cosmic ray showers with energy as low as much possible. Currently, the Tibet array (Tibet-III array) has been accumulating cosmic-ray events at a rate of about 680 Hz. This is about 35 times the Tibet-I array, so that we have enough data to examine a yearly variation of the Sun's shadow by cosmic rays in the multi- and 10-TeV energy region.

It is known that the configuration of solar and interplanetary magnetic fields considerably changes with a cycle of solar activity. We reported that the Sun's shadow was affected considerably by the changing solar and interplanetary magnetic fields (Amenomori et al., 1993b) (Amenomori et al., 1996) (Amenomori et al., 2000). Around the year of

Correspondence to: M. NISHIZAWA (nisizawa@nii.ac.jp)

2000, the solar activity came into a higher state of the major solar variation changing with a 11 year period. The Tibet air-shower array has been continuously operating since 1990 through near a maximum phase in 1991, and a minimum phase around 1996. In the following we report the behavior of the Sun's shadow in a high state of solar activity from 2000 to 2001, and compare it with the previous observation.

2 Solar activity and magnetic field strength

A Sun's shadow by cosmic rays in the 10-TeV energy region is fairly affected by the solar and interplanetary magnetic fields (IMF). The solar magnetic field strength at the source surface (2.5 $R_\odot$) has been observed by the Stanford group and presented as the Stanford Mean Solar Magnetic Field(NOAA/NGDC).

The IMF is formed as a result of the transport of the photospheric magnetic field by the solar wind flowing continuously from the Sun. The IMF near Earth is almost parallel to the ecliptic plane and has Archimedian spiral configuration (Perker, 1963). The strength of Paker field decreases in inverse proportion to the distance from the Sun. The IMF has a sector structure with the field direction reversing across the sector boundary(Wilcox and Ness, 1965), and this well reflects the mean value of source surface magnetic field. The strength and direction of IMF at the Earth orbit are continuously observed by the IMP-8 satellite(NASA/NSSDC).

Monthly variations of the source surface magnetic field (A) and IMF at the Earth's orbit (B) are shown in Figure 1. The form of change of both field strengths is almost same. However, the magnitude of source surface variation from low state to high is three to four times higher than IMF at the Earth's orbit. These figure also show that two solar maximum states and one minimum state occurred around 1990, 2001 and 1997, respectively.

3 Yearly variation of the Sun's shadow

The observation period and characteristic of the Tibet array are summarized in Table 1. The Tibet-II array has about 4.5 times larger effective area than the Tibet-I array. The Tibet-III array operating since November of 1999 has been much improved to detect cosmic ray showers with about 3 TeV, that is, the energy threshold is about $1/3$ of the Tibet-I and Tibet-II arrays.

Cosmic-ray shower data with the Tibet array are collected over 10 years or more. The Sun's shadow around the year of 1991, near solar maximum or at a decreasing phase, was observed at the position fairly away from the apparent center of the Sun (Amenomori et al., 1993a)(Amenomori et al., 1993b)(Amenomori et al., 1996), while it was observed almost in the apparent Sun's direction at around the solar minimum in 1997 (Amenomori et al., 2000). In the previous paper (Amenomori et al., 2000), we discussed why the Sun's shadow in the last solar minimum was found just at the Sun's

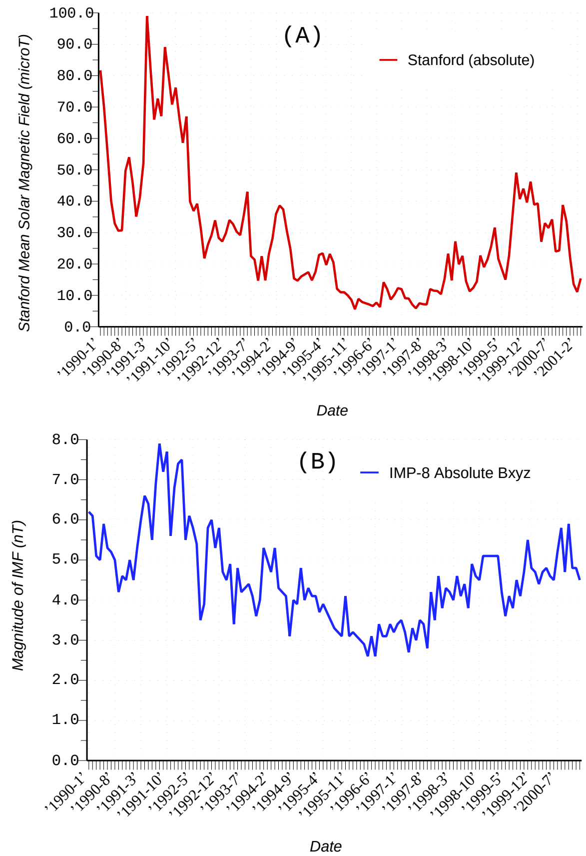

Fig. 1. Monthly averaged magnitude of Solar magnetic field at the source surface observed by Stanford group(A) and interplanetary magnetic field at Earth's orbit by the IMP-8 satellite(B).

position. A remarkable difference of the position of the Sun's shadow is seen between the maximum and minimum phases.

Figure 2 shows a yearly variation of 2-dimensional Sun's shadows in the period from 1991 to 2001. The contour lines start from 0 σ level with 1σ step. Here, we should note the following : (1) event density is different about 7 to 8 times the Tibet-I and Tibet-II data ; and (2) the Tibet-III array has three times lower threshold energy than that of Tibet-I and Tibet-II arrays. The data sets taken in 1998 and 1999 correspond to a rising phase of the solar activity. It is seen that although the event density in the contour map obtained in 1998 and 1999 is almost same as that in 1996-1997 (1.9 to 2.3×10^4

	Start	End	# FT	(Hz)	E(TeV)
Tibet I	June, 90	Sep., 92	45	20	10
	Oct., 92	Oct., 93	45	40	10
Tibet II	Nov., 94	Aug., 95	185	200	10
	Oct., 95	Aug., 96	185	235	10
	Nov., 96	Sep., 99	185	200	10
Tibet III	Nov., 99		497	680	3

Table 1. Observation period, number of fast-timing (FT) detectors, Event rate and mode energy of the air-shower array.

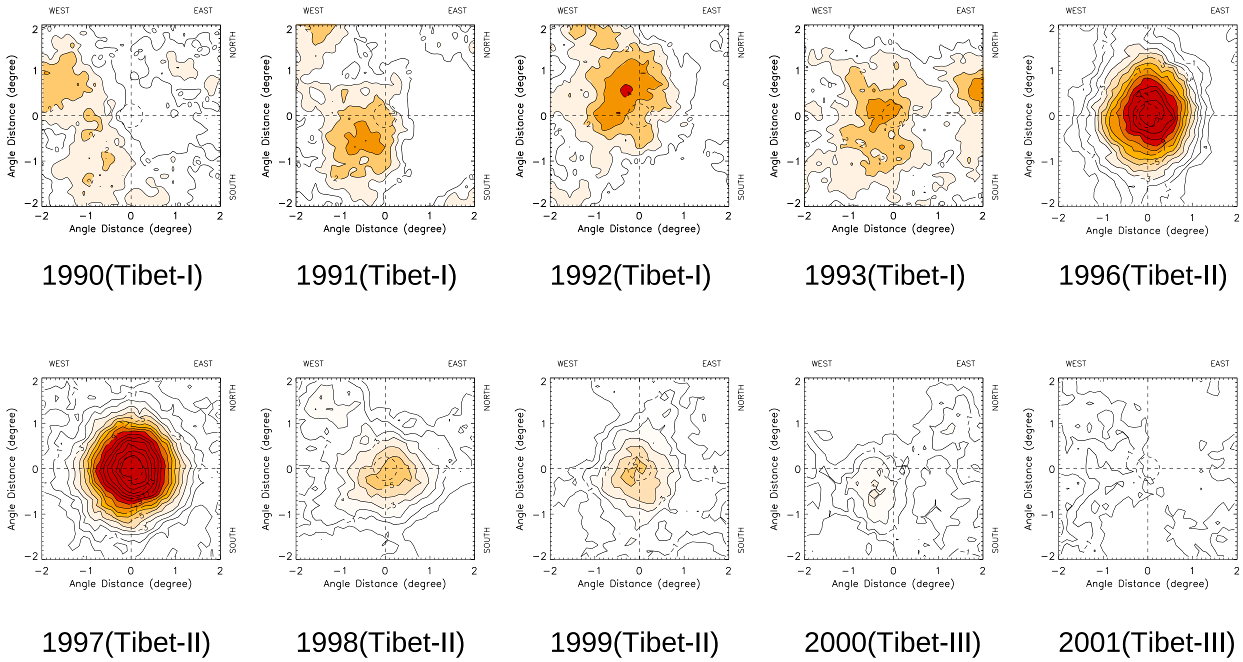

Fig. 2. yearly variation of the Sun's shadow observed by the Tibet-I (1991, 1992), Tibet-II (1996, 1997, 1998, 1999) and Tibet-III (2000, 2001) arrays, respectively. Mode energies are 10 TeV for the Tibet-I, Tibet-II array and 3TeV for Tibet-III array, respectively.

events degree^{-2}), a significance of the Sun's shadow is quite different and it goes to lower. The strengths of source surface magnetic field and IMF increased by about 2.5 and 1.5 times, respectively, in this period. Using the data set obtained with the Tibet-III array in 2000 - 2001, we observed the Sun's shadow by cosmic rays with energies around 3 TeV, which is shown in Figure 2. Surprisingly, the shadows have almost disappeared in this period. This figure tells that the strengths of source surface magnetic field and IMF in 2000 and 2001 increased by 4 and 2 times, respectively. In the active phase, the solar magnetic field near the Sun is far from dipolar and there are many contributions from multi-pole field. Such a complicated field configuration may randomly throw off low energy cosmic rays from the Sun's direction, so that it was complicated shadowless. We need to examine what will happen near the Sun in the active phase using a solar magnetic field model.

4 Sun's shadow at the solar active and quiet state

In order to see the difference of the Sun's shadows at the quiet and active phase in detail, we examined how the the displacement of the shadow depends on the shower energy. The data set was separated into four energy regions according to the size $\sum \rho_{\rm FT}$. They are : $15 < \sum \rho_{\rm FT} < 50$, $50 < \sum \rho_{\rm FT} < 100$, $100 < \sum \rho_{\rm FT} < 300$ and $\sum \rho_{\rm FT} > 300$, respectively. The median shower energy in each size interval is calculated to be 8 TeV, 15 TeV, 35 TeV and 100 TeV in the case of the Tibet-I and Tibet-II arrays, while in the case of the Tibet-III array they are 5 TeV, 9 TeV, 17 TeV and 30 TeV, respectively.

As seen in Figure 3 (A), the shadow shows no obvious displacement. It is of great interest to note that the shadow in the respective energy region was observed almost at the apparent direction of the Sun, independently upon the energy of primary cosmic rays. The observed displacement of the Sun's shadow is a superposition of the effects of the solar magnetic field and the geomagnetic field. The results obtained above suggest that in the quite phase these effects are almost canceled out, resulting in that the shadow remains just at the Sun's apparent position. We examined this hypothesis based on a Monte Carlo calculation. It is known that the solar magnetic field can be approximated by a dipole field in the quiet phase. This simple model can well explain the experimental data mentioned above (Suga et al., 1999)(Amenomori et al., 2000).

Figure 3 (B) shows a preliminary result on the energy dependence of the Sun's shadow obtained with the Tibet-III array in the period from March 2000 to April 2001. In this period, we can not observe any shadow in the low energy region, while in the 10-TeV region, we can see a faint shadow. We should note that the Moon's shadow were clearly observed with a significance of 23σ. Hence, this is due to a complicated configuration of the solar magnetic field in the active phase. We expect that the Sun's shadow becomes clear with a year since the Sun will go into a next quiet phase soon.

5 Summary

We have been continuously observing the Sun's shadow in the period from from 1990 to 2001 with the Tibet air-shower array. We confirmed that the Sun' shadow is well and clearly

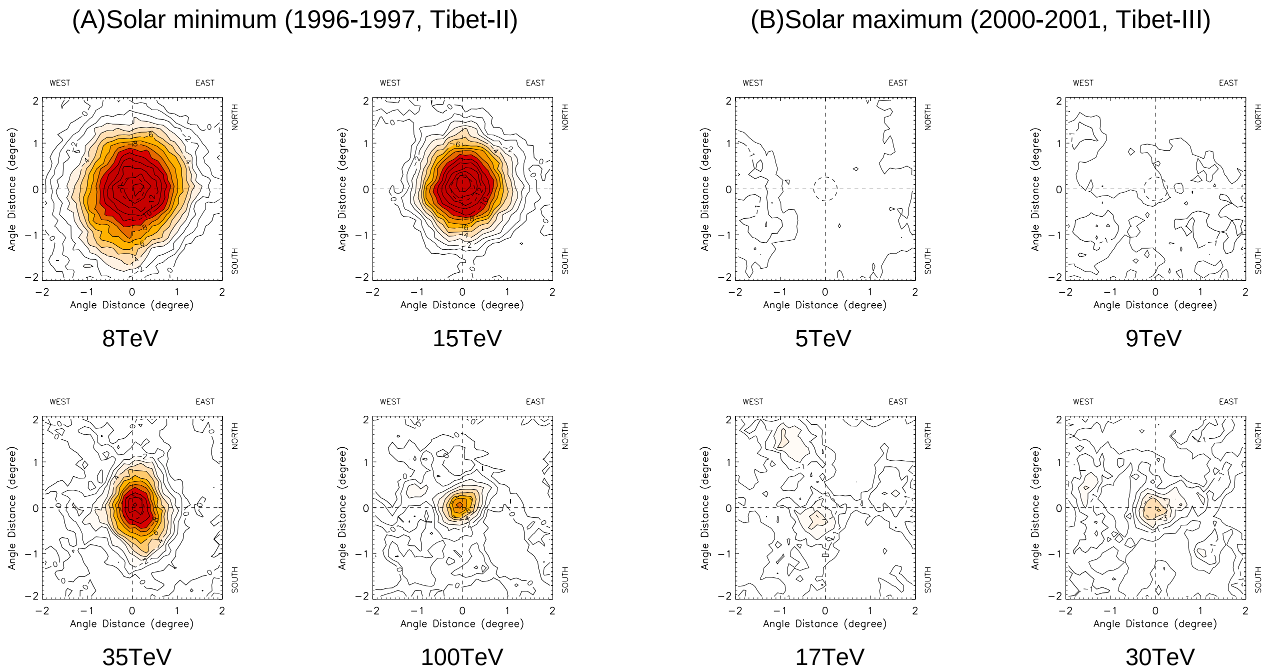

Fig. 3. Comparison of the Sun's shadow at solar lower state (1996, 1997: Tibet-II) and higher state (2000, 2001: Tibet-III) with energy dependence. Note: Median energy is different in (A) and (B).

observed in the quiet phase of solar activity, while it becomes gradually unclear with increasing solar activity and almost disappear around the solar maximum especially in the cosmic ray energy region lower than about 10 TeV. This is very important to estimate what field component affects the position of the Sun's shadow according to a change of solar cycle. We will examine this using a reliable solar magnetic field model and compare with the experiment in the very near future.

Acknowledgements. This work is supported in part by Grants-in-Aid for Scientific Research and also for International Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology in Japan and the Committee of the Natural Science Foundation and the Academy of Sciences in China.

References

Alexandreas, D. E. et al., Physical Review D, **43**, 1735, 1991.
Amenomori, M. et al., Physical Review D, **47**, 2675–2681, 1993.
Amenomori, M. et al., Astrophys. J, **415**, L147-L150, 1993.
Amenomori, M. et al., Astrophys. J, **464**, 954-958, 1996.
Amenomori, M. et al., Astrophys. J, **541**, 1051-1058, 2000.
Amenomori, M. et al., Proc. 27th Int. Cosmic-Ray Conf., OG2.5(This Conf.), 2001.
Fick, B. E. et al., Proc. 21st Int. Cosmic-Ray Conf., **11**, 23, 1991.
NASA/NSSDC, National Space Science Data Center(NSSDC), OMNIWwb - Near Earth Heliosphere Data (http://nssdc.gsfc.nasa.gov/omniweb/).
NOAA/NGDC, National Geophysical Data Center (http://www.ngdc.noaa.gov/).
Parker, E. J., Interplanetary Dynamical Process (New York: Interscience), 1963.
Suga, Y. et al., Proc. 26th Int. Cosmic-Ray Conf., **7**, 202, 1999.
Wilcox, J. M. and Ness, N. F., J. Geophys. Res., **70**, 5973, 1965.