SH 3.2.35

Observation of the Sun's Shadow by High Energy Cosmic Rays in a Quiet Phase of Solar Activity

The Tibet ASγ Collaboration

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ABSTRACT

We have shown that the Sun's shadow by high energy cosmic rays moves year by year and its behavior is related to a time variation of global structure of solar and interplanetary magnetic fields. As well known, the Sun was almost in a quiet phase between 1995 and 1998. In this phase, the direction of equivalent dipole magnetic field of the Sun was almost parallel to the rotation axis of the Sun, while changing its polarity every 11 year. So, if the dipole field strongly affected the Sun's shadow, the shadow would move to westward or eastward direction according to a change of the dipole field direction. We examined this effect using the data set taken with the Tibet-II air shower array during the period from 1995 through 1998. In this paper, we show that the Sun's shadow is sensitive to the solar magnetic field and a long-term observation provides direct information about a change of the solar magnetic field according to the cycle of solar activity.

1. Introduction

The Sun casts the shadow in the cosmic ray flux coming from the direction of the Sun. As almost all cosmic rays are charged particles, they are somewhat bent by the magnetic fields between the Sun and the Earth if their energies are not so high and eventually this effect will make the Sun's shadow shift to a different position from the apparent Sun's direction. This effect was first observed with the

Tibet-I air shower array, constructed at at Yangbajing in Tibet(4300m above sea level), in 1993 [1]. It has also been shown that the displacement of the Sun's shadow is correlated with the cycle of solar activity [2]. When the Sun is in a quiet phase, the solar magnetic field is symmetric between the north and south hemisphere of the Sun. With increasing solar activity, however, the number and the activity of solar active regions tend to increase and these active regions disturb the configuration of the solar magnetic field. This effect can be observed in the Sun's shadow. Actually, the Sun's shadow was observed in the direction shifted considerably from the Sun's direction in 1990-1993 [2]. This period was just in the active phase of solar cycle, so the observed displacement can be attributed to a change of solar magnetic field. The Sun has been in a quiet phase since 1996. Thus, the observation of the Sun's shadow in this period is very important to compare with those observed in the active phase of solar cycle [2] and a comparison of both data may provide direct information about a change of solar magnetic field.

2. Moon's Shadow and Geomagnetic Field

As already discussed in the paper [2], the Moon's shadow provides a good estimate of the angular resolution and systematic pointing accuracy of the air shower array in very high energy region. In the TeV region, the deflection angle of a proton by the geomagnetic field is easily calculated as $\Delta\theta = 1.6^\circ \times (1TeV/E)$ and the direction of this field should make the shadow shift to the west. We first examine this effect in the Moon's shadow observed by the Tibet-II array.

For this, we searched for the deficit center of the Moon's shadow by dividing the events into four size regions of $15 < \sum \rho_{FT} < 50$, $50 < \sum \rho_{FT} < 100$, $100 < \sum \rho_{FT} < 300$ and $300 < \sum \rho_{FT}$, where $\sum \rho_{FT}$ is the sum of the number of particles observed in each detector. The mode energy of protons in each size region is calculated to be 8 TeV, 15 TeV, 35 TeV and 100 TeV, respectively.

Figure 1 shows the event density map of the Moon's shadow in each energy region observed by the Tibet-II array during the period from 1995 to 1998. It is seen that the center of the most deficit point is shifted to the west in lower energy region. These positions are estimated to be $0.25^\circ{}^{+0.09}_{-0.11}$W, $0.08^\circ{}^{+0.09}_{-0.07}$W, $0.04^\circ{}^{+0.04}_{-0.05}$Wand $0.03^\circ{}^{+0.05}_{-0.05}$E, respectively. Here, a maximum likelihood method was used by assuming a 2-dimensional Gaussian type probability function for the event density. These values are consistent with those expected from the geomagnetic field effect.

3. Sun's Shadow

Table 1 shows a yearly variation of the magnitude of solar and interplanetary magnetic fields taken from the data of Stanford Mean Solar Magnetic Field [3] and IMP8 [4]. This table tells us that the strength of IMF near the Earth is rather stable despite changes of solar activity. On the other hand, the mean strength of solar magnetic field reached a maximum around 1991 and then decreased rapidly with decreasing of the solar activity.

Table 1 : Yearly variation of the mean strength of solar magnetic field and IMF near the Earth.

Year	1990	1991	1992	1993	1994	1995	1996	1997
Stanford (μT)	47.0	72.1	34.1	26.4	23.6	14.7	9.1	8.9
IMP8 (nT)	5.1	6.4	5.7	4.4	4.3	3.7	3.1	3.7

As already reported [2,3], the Sun's shadow was observed in the direction shifted to the south-west by about one degree from the Sun's position in the solar active phase of 1990-1993. In this paper, we examine the position of the Sun's shadow observed with the Tibet-II array in quiet solar phase. Shown in Fig. 2 is the energy dependence of the Sun's shadow observed with the Tibet-II array during the period from 1995 to 1998. Each energy region is the same as that in Fig. 1. It is seen that no apparent

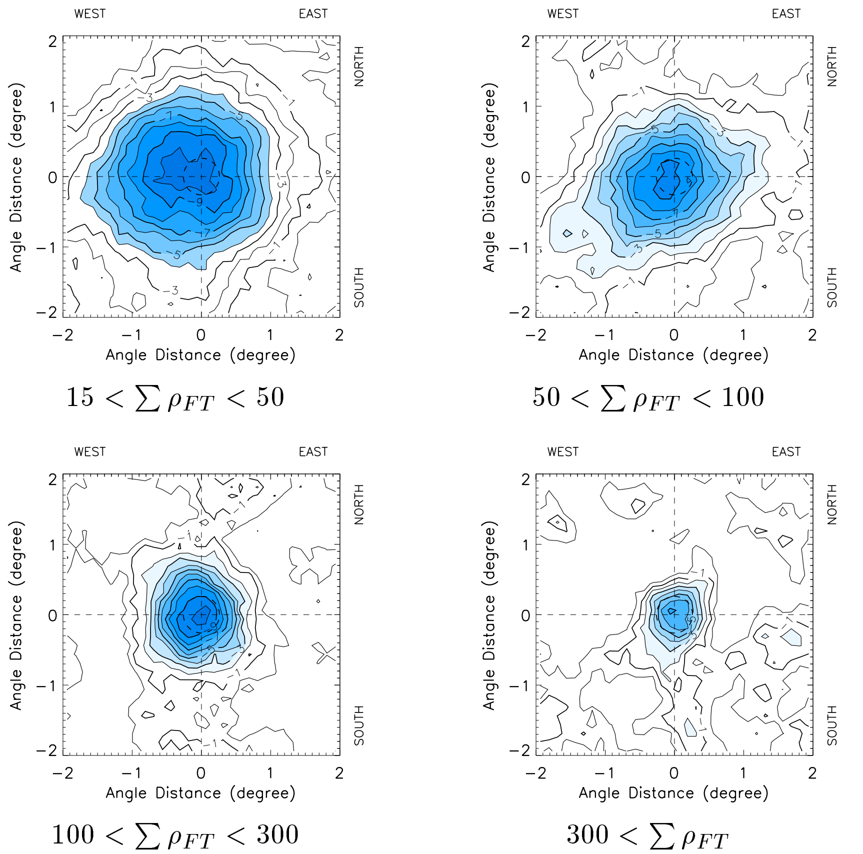

Figure 1: Energy dependence of the displacement of the Moon's shadow. The map of each shadow gives the weight of deficit event density from the background, and contour lines start from 0σ deficit with a step of 1σ.

energy dependence is observed on the position of the Sun's shadow. According to Solar Geophysical Data [3], the N-pole of solar magnetic dipole remained in the north hemisphere of the Sun during the period from 1995 to 1997 so that the polarity of the dipole magnetic field of the Sun in this period made the Sun's shadow shift to the east. Furthermore, a simulation study of the Moon's and Sun's shadows [5] teaches us that if we assume a Sun's dipole field with the magnetic moment of 1.7×10^{32} Gauss$\cdot$cm^3 the displacement of the Sun's shadow by this dipole field becomes almost same as that by the geomagnetic field. On the other hand, the Sun's shadow observed almost in the Sun's direction during this period. Thus, the effect of the solar magnetic field must be apparently canceled by the geomagnetic effect, and eventually this may give a direct estimate of the strength of Sun's dipole magnetic moment. If this is the case, the Sun's shadow will surely move to the west in the next solar minimum as the solar and geomagnetic field effects make the shadow shift to the same direction.

From the very nature of things, if we assume that the N-pole of equivalent dipole field of the Sun was, in an average, in the south hemisphere during this period from 1990 to 1993 with some inclination to the Sun's rotation axis, we can well explain the reason why the Sun's shadow was displaced south-west-wardly in this time. Hence, it is of great significance to follow a change of the position of Sun's shadow over the Solar Cycle 23.

4. Summary

Using the data obtained during the period from 1995 through 1998 with the Tibet-II air shower

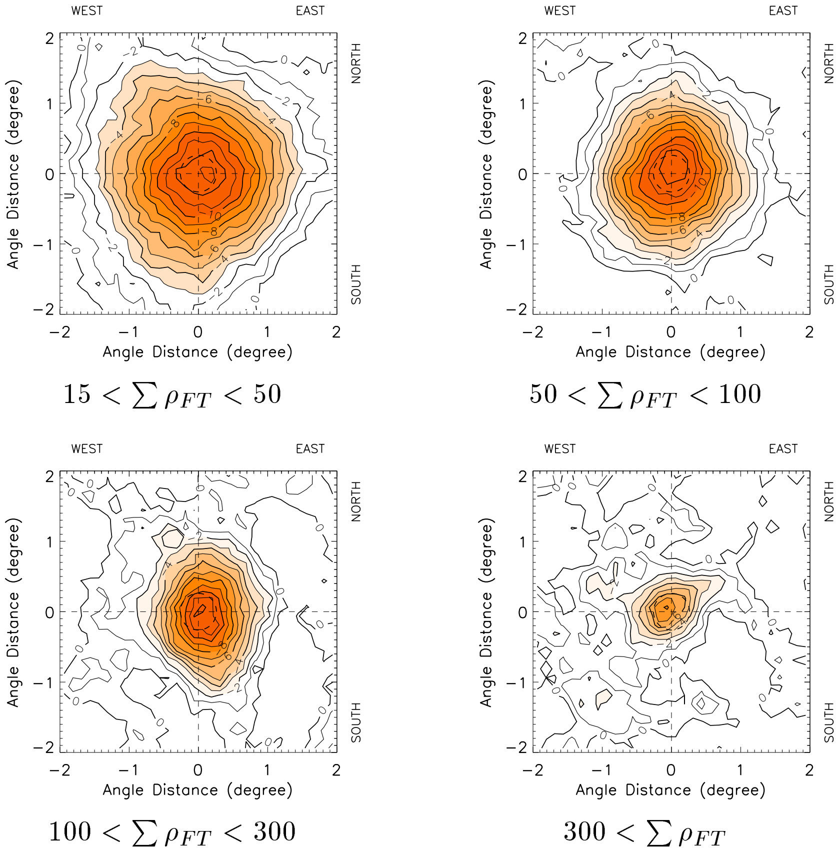

Figure 2: Energy dependence of the displacement of the Sun's shadow. The map of each shadow gives the weight of deficit event density from the background, and contour lines start from 0σ deficit with a step of 1σ.

array, we examined the energy dependence of the cosmic-ray shadows by the Moon and Sun in this period and compared with those observed in 1990-1993. The results suggest that the Sun's shadow is sensitive to the solar magnetic field and its long-term observation may provide vital information about how the solar magnetic field changes with the cycle of solar activity.

Acknowledgments

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

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