Sun Shadows of Cosmic Rays Modulated by Solar Mean Magnetic Field observed with the ARGO-YBJ Experiment

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***Abstract*. The ARGO-YBJ experiment is a large area full coverage detector operating at high mountain altitude (4300 m a.s.l., Tibet, China, 6700 m^2 active surface). Using data obtained during the period from the middle of 2006 to 2008 in a quiet phase of solar activity, the variation of the Sun shadows has been measured with cosmic rays. The correlations between the Solar Mean Magnetic Field (SMMF) and the maximum deficit significance of the Sun shadow, the deficit ratio have been investigated.**

***Keywords*: Sun Shadow, Solar Mean Magnetic Field**

I. INTRODUCTION

Almost all the Galactic cosmic-rays are positively charged particles, and will be somewhat bent under the influence of the solar magnetic field, Interplanetary Magnetic Field (IMF) and geomagnetic field when traveling to the Earth. This will shift the Sun's shadow towards a position away from the apparent Sun's direction. The effect has been observed with the Tibet-I air shower array in 1993 ([1]) for the first time, then the yearly variation of the shift of Sun's shadow ([2]), its north-south displacement in different sectors of the IMF in the quiet phase of solar activity ([3], [4], [5]), and mainly the correlation between the deviation of Sun's shadow and the Solar Mean Magnetic Field (SMMF) have been reported ([6]).

Since is well known that the IMF is formed as a result of the transport of the photosphere magnetic field, we can study the variation of the Sun shadow with the solar magnetic field. From July 2006 to November 2008 solar activity was near its minimum, and the ARGO-YBJ experiment had a good chance to measure the correlations of the SMMF with the maximum deficit significance and the deficit ratio.

II. EXPERIMENT

The ARGO-YBJ experiment, located at the YangBa-Jing Cosmic Ray Laboratory (Tibet, PR China, 4300m a.s.l.), is a single layer of Resistive Plate Chambers (RPCs) ([7]) on a surface of 78 × 74m^2. The central area, consisting of 10×13 Clusters (each of 12 RPCs, each RPC made of 10 Pads) has a full coverage area of 5600m^2 with active area $\sim$ 93%. The guard ring, surrounding the central detector, is designed to discriminate the inner against outer events. The detector has two different DAQs, "scaler mode" ([8]) and "shower mode". In shower mode, the data have been collected with the central carpet since July 2006, with the trigger condition $N_{hit} \geq 20$, where N_{hit} is the number of fired Pads in the trigger window of 420 ns. In this case, the trigger rate for air shower events is $\sim$3.6 kHz.

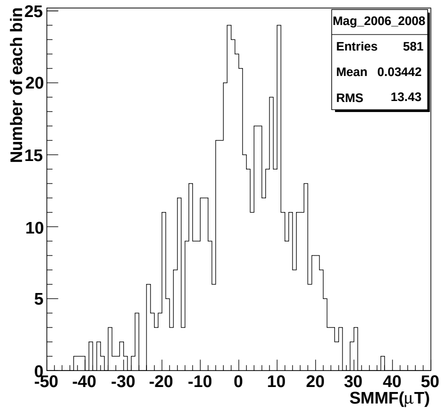

Fig. 1: The distribution of SMMF values from 2006 June to 2008 November

We analyzed the data set during the period from July 2006 to November 2008, selecting events in a circle of radius 7° around the Sun, with zenith angle less than 50°, reconstructed core position less than 150 m, Chi square of reconstructed shower front less than 200(ns)^2 and number of fired Pads on the carpet larger than 100. A coordinate system was fixed on the source investigated, putting the origin of coordinates on its center. The Equi-Zenith angle method ([9]) in equatorial coordinates is used for background estimation for both the Sun and the Moon.

A measurement of the solar magnetic field can be done by a Babcock-type magnetograph attached to a 23 m vertical Littrow spectrograph at Stanford Solar Observatory ([10]). Several observations are made daily, centered around local noon. Each integer value reported is a weighted average of all measurements for that day. The weighting arises from effects that include solar rotation, limb darkening and weakening of the sensitive absorption line within active regions. Fig. 1 shows the distribution of the SMMF observed from 2006 July to 2008 November, when ARGO-YBJ was

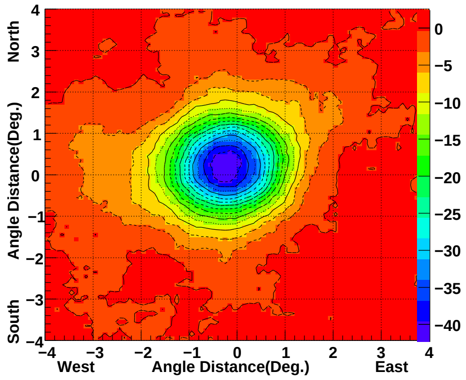

Fig. 2: Map of the deficit event densities around the Moon in the area $8^{\circ} \times 8^{\circ}$ centered on the Moon during the period from 2006 July to 2008 December

taking data in normal operation. A negative value means that the SMMF is directed towards the Sun, whereas a positive value means the SMMF is directed away from it.

III. Moon's Shadow and Geomagnetic field

As discussed in ([1]), the Moon's shadow provides a good estimate of the angular resolution and systematic pointing accuracy of the air shower array at higher energies. With this method the angular resolution obtained for the ARGO-YBJ experiment when $N_{hit} \geq 100$ is better than 1°, and the median energy of the primary cosmic rays generating the air showers detected by the array is estimated to be 4.0 TeV for protons ([11]).

Fig.2 shows the deficit event significance map of the Moon's shadow, obtained using the events observed during the period from 2006 July to 2008 December. It can be seen that the center of the Moon's shadow is shifted towards west and north. The coordinates of the maximum deficit events are estimated to be $0.21^{\circ} \pm 0.03$ west and $0.21^{\circ} \pm 0.03$ north.

IV. Sun's Shadow and Solar mean magnetic field

The ARGO-YBJ data set was divided into 12 subsets according to the SMMF distribution listed in TABLE I. Some deficit event significance maps of the Sun's shadow are shown in Fig. 3. The observed displacement of each Sun's shadow is a superposition of the effects of the solar magnetic field and geomagnetic field. It is very interesting to note that the shadow gradually shifts towards north away from the apparent Sun's position when the SMMF decreases towards the Sun and increases away from it.

A. *Deficit significance Vs. SMMF*

In order to measure the deficit of cosmic rays due to the Sun, the number of events detected in a circular window of radius R=1.2° around the Sun position is compared with the expected background. The significance of the event deficit is calculated as S=(N_{on}-N_{off})/$\sqrt{N_{on} + N_{off}/6}$, where N_{on}(N_{off}) is the total number of events in the on (off) source windows. The off-source windows are 6, with the same size and zenith angle of the on-source one. The maximum deficit significance has been normalized to the events number in the range -1≤SMMF≤ 0 listed in TABLE I. Fig. 4 shows the good correlation between the maximum deficit significance level and the SMMF variation. This can be explained as more cosmic rays can be modulated when the SMMF is larger, corresponding to a more intense solar activity.

B. *Deficit ratio Vs. SMMF*

The deficit ratio, that is the number of observed deficit events due to the Sun shadow divided by the number of the expected deficit events, is a non-dimensional quantity and independent of the exposure, which can better reveal the solar activity. The expected deficit events number, calculated by the background from the apparent Sun size, is not affected by solar activity. it can be approximatively obtained by the following formula :

$$N_{def} = \eta \times N_{sun} \tag{1}$$

$$\eta = 1 - e^{-0.5 \times (R/\sigma)^2} \tag{2}$$

where N_{sun} is the number of events intercepted by the Sun, R is the radius of the observation circular windows and σ is the Gauss distribution width from the Moon shadow obtained with the ARGO-YBJ experiment ([11]). The good correlation between deficit ratio and SMMF is shown in Fig. 5, where the largest value is not 1 because the SMMF is just the line-of-sight component of the solar magnetic field, not including the transverse components.

V. Summary and Discussion

Using the data obtained during the period from 2006 June to 2008 November with the AROG-YBJ experiment, we have concluded that the maximum deficit significance and deficit ratio have a clear correlation with the SMMF. The solar cycle is now in a quiet phase, and observations with higher statistics will be done in the very future.

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TABLE I: SMMF and the other variables.

range(μT)	[-43,-20]	[-19,-13]	[-12,-8]	[-7,-4]	[-3,-2]	[-1,0]	[1,3]	[4,6]	[7,9]	[10,12]	[13,17]	[18,46]
Duration(days)	48	44	39	51	40	36	38	42	36	40	40	35
mean value(μT)	-26.7	-15.7	-10.1	-5.0	-2.4	-0.5	1.9	4.9	7.9	10.7	15.2	22.8
Events(10^6)	5.78	4.68	3.93	5.31	4.57	3.99	4.44	5.21	3.16	4.56	4.12	2.43
Max. sig.(σ)	-9.5	-11.8	-9.1	-10.8	-11.6	-10.8	-10.8	-11.2	-9.2	-9.0	-8.1	-5.6
Ratio	0.56	0.75	0.64	0.67	0.81	0.80	0.78	0.75	0.73	0.57	0.56	0.42
Ratio-erro	0.01	0.014	0.014	0.013	0.015	0.016	0.015	0.014	0.017	0.012	0.012	0.013

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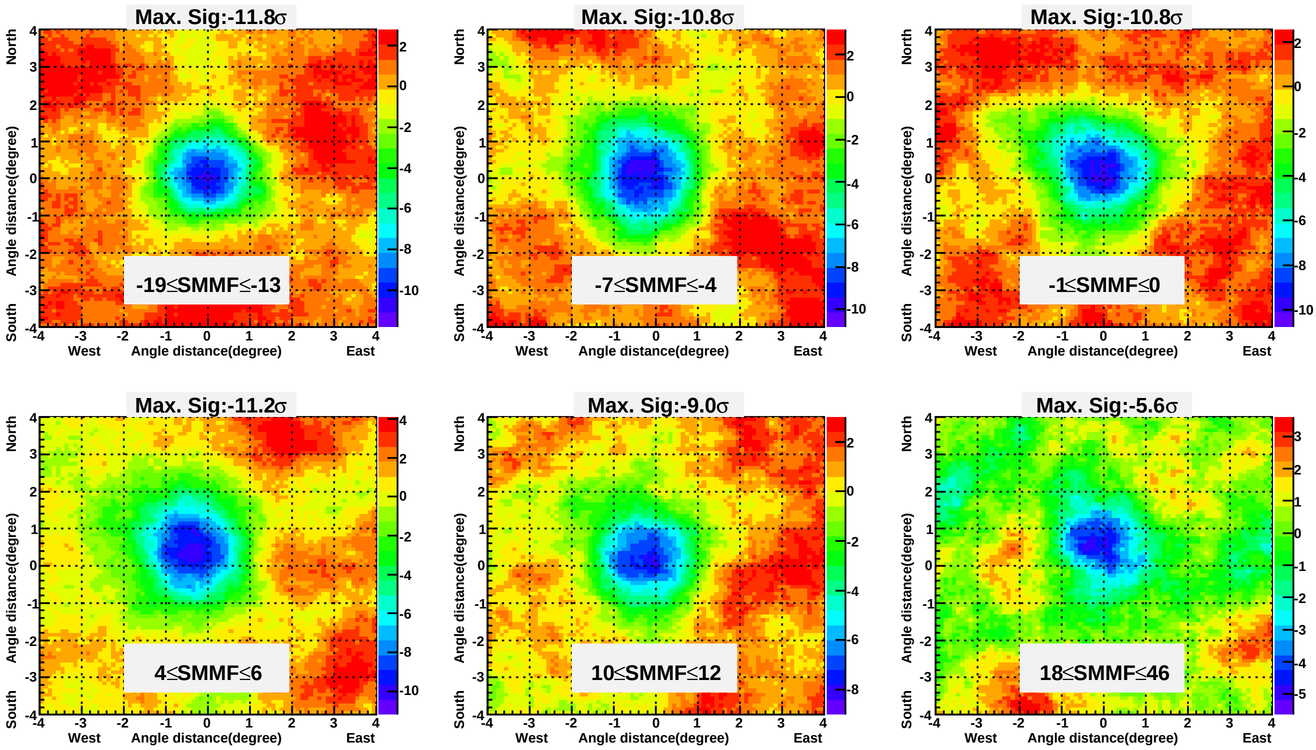
The Duration gives the number of days when the SMMF was in the corresponding range and ARGO-YBJ data were available.



(a)

Fig. 3: Sun's shadow in different SMMF ranges.

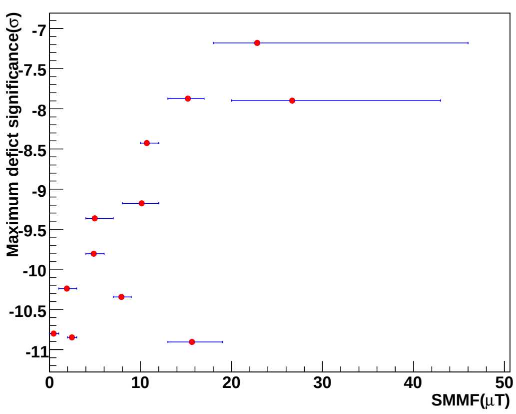


Fig. 4: Correlation between the maximum significance and SMMF (the significance has been normalized,see text for details)

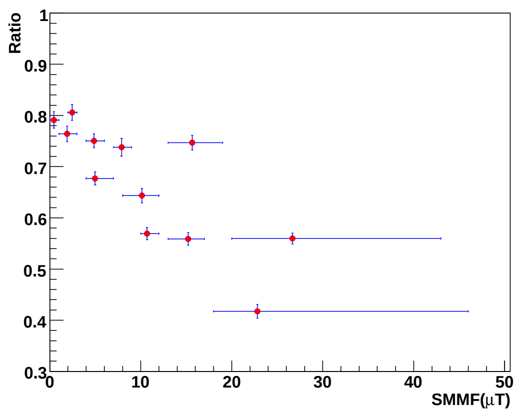


Fig. 5: Correlation between the deficit ratio and SMMF

REFERENCES

[1] Amenomori, M. et al. Phys. Rev. D. 47 (1993) 2675

[2] Amenomori, M. et al. Advances in Space Research 38(2006)936-941
[3] Amenomori,M. et al. The Astrophysical Journal, 464(1996)954-958
[4] Liu Shaomin et al. High Energy Physics and Nuclear Physics,21.10(1997)865-871
[5] Amenomori,M. et al. The Astrophysical Journal, 541(2000)1051-1058
[6] Lu Hong et al. High Energy Physics and Nuclear Physics,23.4(1999)313-319
[7] G. Aielli et al. Nucl. Instr. Meth., A562 (2006) 92
[8] G. Aielli et al. Astroparticle Physics 30 (2008) 85
[9] Amenomori, M. et al. The Astrophysical Journal, 633(2005)1005-1012
[10] http://wso.stanford.edu/
[11] G. Di. Sciascio et al,these proceedings.