



Sun Shadow study in the quiet phase of the solar activity with the ARGO-YBJ experiment

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Abstract: The sun is still in its quiet phase and the ARGO-YBJ experiment accumulates more data for sun shadow analysis. In this paper, firstly we will introduce the displacements in west-east direction of the sun shadow with the higher statistic significance as a function of the time, which is probably correlated with the solar polar magnetic field measured at Wilcox Solar Observatory. The deficit ratio of the sun shadows as a function of the time are also presented, which indicates the solar activity is going towards active.

Keywords: cosmic rays, sun shadow, solar activity, the ARGO-YBJ experiment

1 Introduction

Cosmic rays from outside the solar system, mainly hydrogen and helium nuclei[1], isotropically arrive at the Earth and can be recorded by detectors on the ground, such as the resistive plate chamber array in the ARGO-YBJ experiment[2] at 4300 m above the sea level in Tibet, China. At energies around 5 TeV, the cosmic-ray arrival directions are measured by the ARGO-YBJ detector with accuracy better than 1° [3]. The distribution of particle counts on the sky shows a deficit corresponding to the location of the Sun's shadow. The solar magnetic Field, interplanetary magnetic Field, and geomagnetic field along the trajectories deflect these rays slightly and shift the shadow from the true location of the Sun. The Tibet AS γ experiment observed the effect for the first time [4]. This experiment also observed the core of the sun shadow shift toward east is probably because of the solar dipole magnetic field in 1996 and 1997[5]. What is measured using the deflection of cosmic rays is a cumulative effect along the whole path from the Sun to the Earth. Using the shift in the south-north direction of the shadow, the ARGO-YBJ experiment has measured the intensity of the field that is transported by the solar wind from the Sun to the Earth for the first time in the minimum of the solar activity[6]. If the magnetic fields on the surface of the sun (SMF) are very irregularly distributed, particles passing through the surface follow totally different paths highly dependent on the local distribution of the fields. The deflections could be so randomly that the particles could be smeared back into the direction of the sun. As a consequence, the deficit of cosmic ray flux in the shadow is reduced. When solar activity increases to an certain extent, the sun shadow observed in the quiet

phase will disappear. In this paper, the topic are the shift of the sun shadow in the west-east direction and deficit ratio during the period from 2008 through 2010.

2 The ARGO-YBJ Experiment

The ARGO-YBJ experiment, located at the YangBaJing Cosmic Ray observatory (Tibet, China, 4300m a.s.l.), is a single layer of Resistive Plate Chambers (RPCs) on a surface of $78 \times 74\text{m}^2$. The central part has a full coverage area of 5800m^2 with 10×13 clusters which have 12 RPCs in each and each RPC has 10 pads. It is used for event triggering. At the skirts of the array, so-called guard ring made of 23 clusters with a coverage of 25%, is designed to select inner events whose cores of showers are falling inside the array. Cosmic ray data have been collected with a trigger criterion of $N_{\text{hit}} \geq 20$, where N_{hit} is the number of fired Pads in a trigger window of 420 ns, since July 2006. The trigger rate for air shower events is $\sim 3.5\text{kHz}$.

Cosmic ray data from 2008 to 2010 is analyzed for this work. Events in a cone of 6° respect to the sun and zenith angle less than 50° are selected. Further criteria include that reconstructed core positions must be within a distance of 150 m to the center of the array, that the least χ^2 of reconstructed shower front must be less than $200(\text{ns}^2)$ and that of the number of fired pads on the carpet must be greater than 100. 1.06×10^8 events survived the cuts. According to the absolute energy scale calibration carried out with the moon shadow analysis, the median energy of the selected data set is approximately 5TeV[3].

Applying the same cuts to data around the Moon, as discussed in[3], one estimates the angular resolution of the

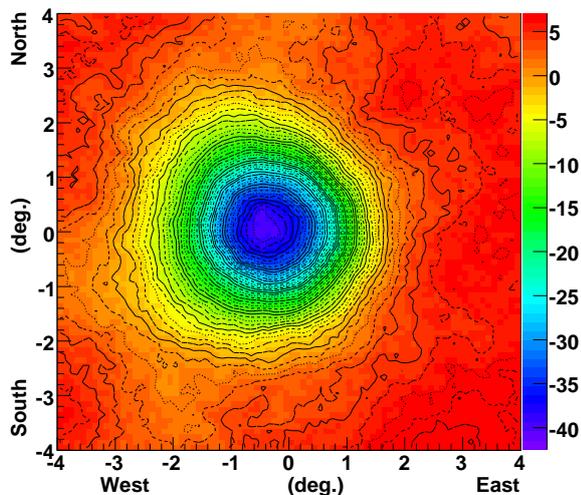


Figure 1: Sun shadow measured using all the data taken by the ARGO-YBJ experiment from 2008 through 2010. This map is based on a 2D histogram on a grid of $0.1^\circ \times 0.1^\circ$ with a smoothing within a circular bin of 1.2° as its angular radius which takes into account the point-spread function of the ARGO-YBJ detector. The central circle of the contour map indicates a significance of 41.4 standard deviation of the deficit in event count. The step between contour lines is one standard deviation. The maximum significance is 42.4 standard deviation.

ARGO-YBJ detector to be better than 1° . In order to estimate how significantly the shadow is measured, a cosmic ray background flux in the direction of the Moon and the Sun are estimated using a so-called equi-zenith angle method in ref[7].

3 Sun Shadow Analysis

In Figure 1, We show the deficit event significance map of the sun shadow with the most significant point (43.2σ , using Li Ma formula ([8]) for the significance estimation) located at $(0.10 \pm 0.03)^\circ$ toward north and $(0.32 \pm 0.03)^\circ$ toward west. The observed displacement of the shadow in the figure is a superposition of the effects of the solar magnetic field, interplanetary magnetic field (IMF) and the geomagnetic field. In order to understand the effect of the geomagnetic field, the same selection criteria are applied to events around the Moon. With a significance of 63σ , the location of the moon shadow is $(0.10 \pm 0.02)^\circ$ toward north and $(0.32 \pm 0.02)^\circ$ toward west, which is stable during the short period due to the geomagnetic field.

It is known that near solar minimum the solar magnetic field is symmetric between the north and south hemisphere of the Sun and the neutral sheet is laid on the ecliptic plane with relatively small warp. It will scarcely make the Sun's shadow shift to the east-westward. Therefore, the displace-

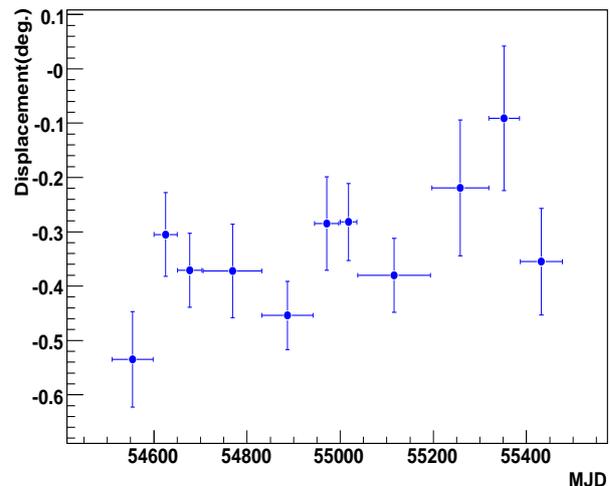


Figure 2: Shift of the center of the Sun shadow along the west-east direction as a function of the time from 2008 through 2010. The horizontal axis gives the MJD and the vertical axis is the angular displacement along the west-east direction of the center of the shadow.

ment in west-east direction of the sun shadow is mostly attributed to the solar dipolar field and the geomagnetic magnetic field.

In order to study the relation between the sun shadow with the solar dipole magnetic field and the sun spots, the ARGO-YBJ data mentioned above are divided into 11 groups. The observation period using Modified Julian Date style for each shadow is as follows: 54510-54598, 54599-54650, 54651-54705, 54706-54831, 54832-54944, 54945-54998, 54999-55037, 55038-55196, 55197-55319, 55320-55387, 55388-55478. Each group has approximately 10 million events which measure the shadow with an average significance of about 13σ .

3.1 Shift of the center along the west-east direction from 2008 to 2010

The positions of all the 11 shadows are measured by projecting the two-dimensional (2D) map onto the axis along the west east direction and fitting it with a Gaussian functional form. A $\sim 0.4^\circ$ shift of the sun shadow over a range greater than as shown in Figure 2. The westernmost position of the shadow is about 0.3° in the year 2008, which is the period of the solar minima. The easternmost position is about 0.1° , removing the geomagnetic field effect.

3.2 Deficit ratio from 2008 to 2010

The deficit ratio of the sun shadow means the ratio of the observed deficit count to the expected one. It is a non-dimensional quantity and is independent of the exposure,

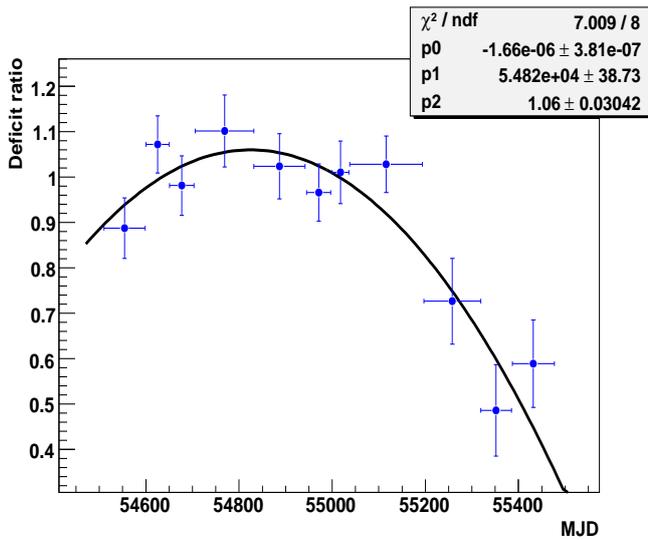


Figure 3: The deficit ratio of the observed deficit count to the expected one as a function of the observation time. The curve is a fit with a polynomial function.

which can better reveal the solar activity. The expected number of deficit can be estimated by

$$N_{def} = [1 - e^{-0.5 \cdot (\frac{R}{\sigma})^2}] \cdot N_{sun}$$

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 Gaussian distribution width from the moon shadow obtained with the ARGO-YBJ experiment[3]. Figure 5 shows that the deficit ratio increased slowly and reached its the maximum when the time is $\text{MJD } 54820 \pm 38.73$ day, and then decreased.

4 Discussion on correlation

Large-scale solar magnetic field (and its various resulting in the solar cycle) is the product of various physical mechanisms acting decaying solar active region. And it is widely believed that solar magnetic field modulate the cosmic ray flux intensity in a solar cycle. The correlation between the flux deficit ratio of the sun shadow and solar mean magnetic field have been reported by the ARGO-YBJ experiment[9]. Here, we will discuss the possible correlation between the sun shadow and the solar dipolar magnetic field, the sun shadow and sunspots.

4.1 sun shadow Vs. solar dipole magnetic field

The dipolar magnetic field measurement is difficult from the ecliptic plane due to the weakness of the polar magnetic field, and the solar geometry close to the limb. A ground-based measurement can be done by Wilcox Solar Observatory, which is the projected component of the photospheric

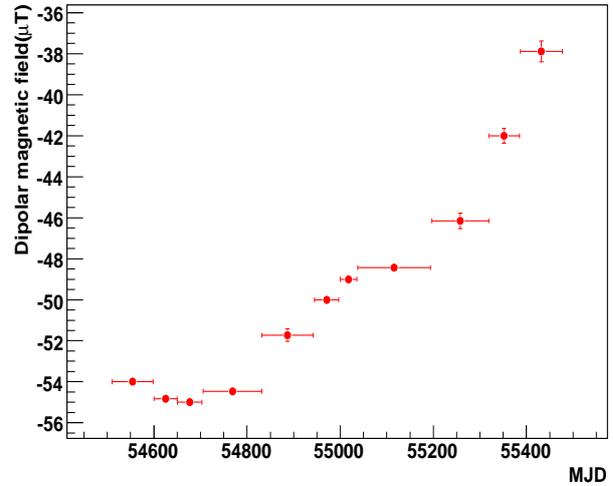


Figure 4: The solar dipole magnetic field as a function of the measurement time from 2008 through 2010. The horizontal axis gives MJD and the vertical axis is the strength of solar polar magnetic field. The data is downloaded from the Wilcox Solar Observatory[12]

magnetic fields poleward of about 75 degree latitude. In each 10 days the usable daily polar field measurements in a centered 30-day window are averaged which is showed in Figure 4. It clearly shows that the dipolar magnetic field slowly decreased when the solar activity increased from 2008 through 2010. According to ref[10], in the year 2008, 2009 and 2010, the polarity of the solar dipole magnetic field was inward in the northern hemisphere and outward in the southern hemisphere, that is N-pole of the solar dipole in the southern hemisphere. Therefore, the core along the west-east direction of the shadow shifts toward west in the solar minima. with the solar activity active, the solar magnetic field turned more irregularly, the strength of solar dipole magnetic field decreased, the core of the shadow did not turn towards west as what happened like in Figure 2.

Another reason why the shift to the east direction during three years may contribute to the more and more lower energy particles smeared into the direction of the Sun with the solar activity being more and more intensive, which is under careful research.

4.2 Correlation between the deficit ratio and sunspots

Sunspots appear as dark spots on the surface of the Sun. Temperatures in the dark centers of sunspots drop to about 3700 K (compared to 5700 K for the surrounding photosphere). Sunspots are magnetic regions on the Sun with magnetic field strengths thousands of times stronger than the Earth's magnetic field. Sunspots usually come in groups with two sets of spots. One set will have positive or

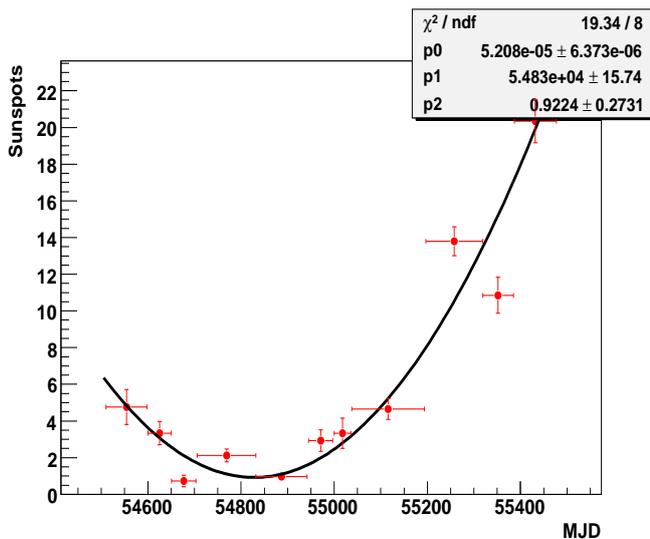


Figure 5: The sun spots as a function of the measurement time from 2008 through 2010. The horizontal axis gives MJD and the vertical axis is the number of the sunspots. The curve is a fit with a polynomial function.

north magnetic field while the other set will have negative or south magnetic field. Therefore, the larger the number of sunspots is, the more active the sun becomes. The sunspots data in the Figure 5 are downloaded from Solar Influences Data Analysis Center. by comparing Figure 3 with Figure 5, It shows that deficit ratio decreased when the sunspots number increased, and they arrived at their extreme value almost in the same time. Moreover the correlation probability is 99.99%, and the correlation coefficient is -84%. Therefore, they have a good anti-correlation. When the sunspots increase, meaning a more intensive solar activity, more and more cosmic rays are smeared into the direction of the sun due to the more complex solar magnetic field.

5 Summary and Discussion

Using the data obtained with the ARGO-YBJ experiment during the period from 2008 through 2010, we study the sun shadow with higher statistical significance. In this period, we discuss the possible correlation between the displacements in the direction of west-east of Sun's shadow and the solar dipole magnetic field. Also the good anti-correlation between the deficit ratio and the sunspots confirmed that the solar activity decreased gradually in Solar Cycle 23 and increased in Solar 24.

The Sun is now going toward the active phase of the Solar Cycle 24 and will reach a maximum in the near future. Then, the angle of the dipole component should rotate from south to north, reversing near maximum. The behavior of the dipole may be directly examined from the observation of the Sun's shadow during the period near maximum.

Although the ARGO-YBJ detector does not has a sufficient sensitivity to measure the sun shadow with the required precision in a single day, a future detector such as the LHAASO project[13], may be sensitive enough to be able to measure the Sun shadow within 1 day or so. Thus, it would be practically useful in monitoring unexpectedly large shifts of the Sun shadow to monitor solar activity.

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