Preliminary results on the Moon shadow with ARGO-YBJ

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Abstract: ARGO-YBJ is a "full coverage" air shower detector consisting of a carpet of Resistive Plate Chambers, located at Yangbajing, Tibet, China, at 4300 m of altitude. Using the data collected from July 2006 to Februay 2007 by the central detector (5800 m^2 area), corresponding to a total time of Moon observation of 558 hours, the cosmic ray shadowing effect has been detected with a statistical significance of $\sim$10 standard deviations,in agreement with Montecarlo expectations.

Introduction

The idea of observing the shadowing effect of the Moon on the cosmic ray flux was originally suggested by Clark[1] in 1957, but only 35 years later the first successful observation was reported. The bending of the charged cosmic rays due to the geomagnetic field ($\sim 1.6^\circ$ TeV^{-1}) smears the shadow at low energy, and make possible the observation of the effect only at relatively high energies. Moreover a very good angular resolution of the detector[2] and high statistics are necessary conditions to detect the deficit of events in the cosmic ray flux. The first observation of the Moon shadow was made by the CYGNUS air shower array in 1992[3], followed by other experiments such as CASA, Tibet-ASγ, EASTOP, HEGRA, MACRO, L3+C and MILAGRO.

The Moon shadow is an important tool for ground-based detectors. The spread and the shape of the shadow at energies where the geomagnetic effect is small, provide a measurement of the angular resolution of the detector, and the position of the shadow allows to find out possible pointing biases. The observation of the Moon shadow can also be used to perform an absolute energy calibration of air shower arrays[4].

From the astrophysical point of view, the Moon shadow allows the study of the $\bar{p}$ content of cosmic rays in the TeV energy range, thanks to the geomagnetic deflection of primary particles[5, 6]. Positively charged primaries are deflected towards the West, while negatively charged ones towards the East. If antiprotons are present in cosmic rays, they will generate a shadow on the opposite side of the Moon position with respect to the shadow made by the dominant proton flux.

The ARGO-YBJ experiment

The ARGO-YBJ detector consists of a single layer of Resistive Plate Chambers (RPCs) of dimension 78 $\times$ 74 m^2, surrounded by a sampling ring ($\sim$1050 m^2, equipped area $\sim$20 %)[7]. The detector is logically divided into 154 units called Clusters (7.6$\times$5.7m^2), each made up of 12 RPCs operated in streamer mode. Each RPC (1.3 $\times$ 2.9 m^2) is divided into 10 pads (62 $\times$ 56 cm^2), that are read out by 8 strips (62 $\times$ 6.7 cm^2), providing the highest available space resolution. The whole system is designed to provide a single hit (pad) time resolution at the level of 1 ns, allowing a complete and detailed space-time reconstruction of the shower front. In order to convert a fraction of the secondary gamma rays into electron-positron pairs and to reduce the time spread of the shower front improving the angular resolution, the detector will be covered by a 0.5 cm thick layer of lead.

Since July 2006, the central detector of 130 Clusters (ARGO-130) has been operating with a multiplicity trigger $N_{pad} > 20$, with a rate of $\sim$ 4 kHz.

In this work, the data sample collected from July 2006 to February 2007 with ARGO-130 have been used. In total the Moon has been observed for 558 hours.

The shower direction is reconstructed by means of an iterative procedure, assuming that the shower front has a conical shape, with a fixed cone slope of 0.03 ns m^{-1}[8]. The relative time offsets among different pads have been calibrated with the method described in[9, 10].

In our analysis, the event selection was done by imposing the following criteria on the reconstructed data:

(1) The reconstructed core position should be located inside the array;

(2) The number of fired pads N_{pad} should be larger than 500 (corresponding to a median energy of $\sim$5 TeV);

(3) The zenith angle of the incident direction should be less than $45°$.

After these cuts, 2.2×10^5 events in a window of $6° \times 6°$ centered on the Moon position have been selected.

Data analysis

To measure the deficit of cosmic ray from the Moon, the number of events detected in a circular window of radius $R = 0.8°$ around the Moon position is compared with the expected background.

The significance of the event deficit is calculated as $S = (N_{on} - N_{off})/\sqrt{(N_{on} + N_{off}/6)}$.

$N_{on}(N_{off})$ is the total number of events in on(off) source windows. The off-source windows are 6 windows having the same size and zenith angle of the on-source one.

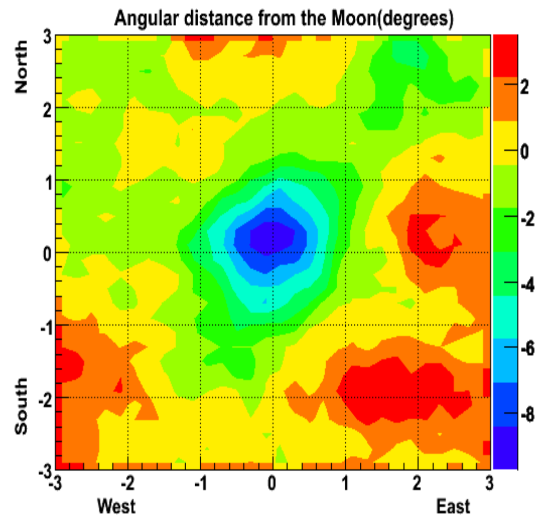

Figure 1: The significance map of the Moon shadow obtained in 558 hours of observation, selecting the events with a number of fired pads larger than 500.

Fig.1 shows the significance map of the Moon shadow from ARGO-130 data. A peak of $\sim$10 standard deviations can be seen, shifted by $0.04°$ toward the West and $0.14°$ toward the North with respect to the nominal Moon position.

From the spread of the deficit distribution in the North-South direction, where the geomagnetic effect is almost negligible, we can evaluate the angular resolution of the array.

Fig.2 shows the distribution of the observed deficit events projected along the W-E and N-S axes. The data points can be well fitted by a Gauss distribution. The Gauss width is $\sigma_{E-W} = 0.43° \pm 0.07°$ for the W-E distribution and $\sigma_{N-S} = 0.51° \pm 0.09°$ for the N-S distribution.

The N-S width is in good agreement with the values of the angular resolution obtained by other methods[11].

Fig.3 shows the cumulative number of deficit events plotted as a function of the Modified Julian Date (MJD), during 8 months, compared with the expected one. The expected number of deficit events N_{def} is approximatively given by:

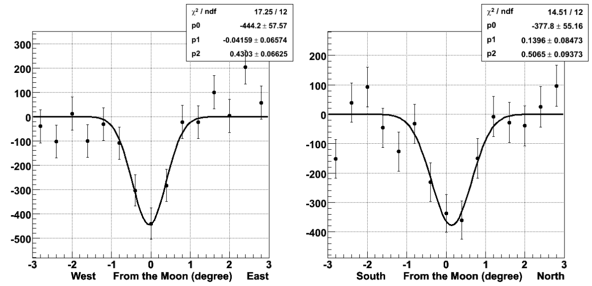

Figure 2: Distributions of the number of events of the observed deficit projected along the W-E and N-S axes, superimposed to the best fitted Gauss functions, with width respectively $\sigma_{E-W} = 0.43° \pm 0.07°$ and $\sigma_{N-S} = 0.51° \pm 0.09°$.

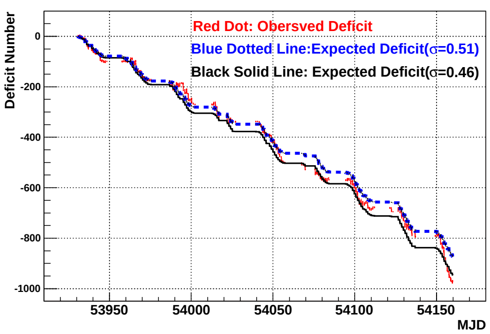

Figure 3: The number of missing events compared to the expectation, as a function of time (days in Julian Date), during 8 months of data taking.

$$N_{def} = \eta \times N_{moon} \qquad (1)$$

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

where N_{moon} is the number of events intercepted by the Moon, R is the radius of the observation circular window, and σ is the Gauss distribution width. In the figure the expected deficit has been calculated for $\sigma = \sigma_{N-S} = 0.51°$ and for $\sigma = 0.46°$, i.e. the average between σ_{E-W} and σ_{N-S}. Data are in good agreement with expectations, indicating the stability of the array operation.

Monte Carlo simulation

A detailed comparison between the position and the significance of the observed deficit and the expected one has been performed by a full simulation procedure.

The IGRF model[12] was chosen to describe the geomagnetic field for altitude smaller than 600 km and the dipole model (dipole moment M=8.07 $\times$ 10^{25} Gauss cm^3) for altitude above 600 km.

The primary particles are assumed to be protons with a differential power law spectrum as $E^{-2.7}$ with energy ranging from 1 TeV to 1000 TeV.

The simulated events are generated on the top of the atmosphere, randomly distributed along the Moon's orbit during the observation period. Then, we reverse the charge of each event and shot it back toward the Moon, taking into account the deflection due to the geomagnetic field.

The events hitting the Moon are collected as the "missing events" and are studied in detail, simulating the cascade in atmosphere (using the CORSIKA6200 -QGSJET package[13]), the detector response (using a package based on GEANT-3) and performing the standard event reconstruction. After all, 1260 "missing events" survive the event selection criteria.

To save CPU time, the angular distribution of background events was directly taken from the observation.

Whith this method we performed 1000 toy Monte Carlo experiments and for each we calculated the position and the significance of the shadow.

The distribution of the significance of the simulated deficits are shown in Fig.4. The experimental significance is in agreement with expectations.

The distribution of the position of the shadow centers are shown in Fig.5. The mean position of the shadow center is shifted toward the West by $\sim 0.3°$, due to the geomagnetic deflection.

The position of the center of the observed shadow shows a shift of $\sim$0.25° with respect to the expected position.

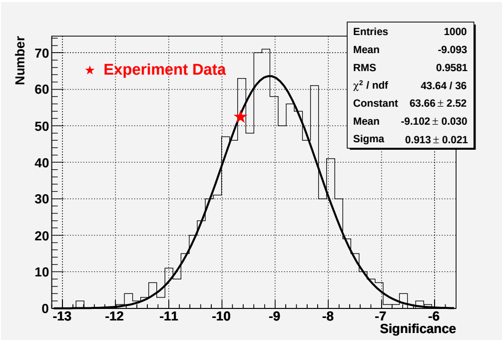

Figure 4: The significance distribution of the Moon shadows obtained in 1000 toy Monte Carlo experiments. The red star is the observed significance.

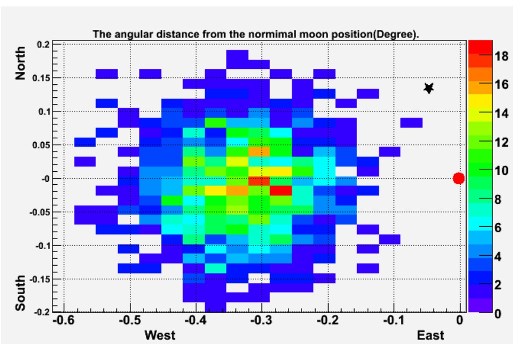

Figure 5: The distribution of the simulated Moon shadow centers. The red circle is the Moon position and the black star is the observed position of the Moon shadow center. The color scale indicates the number of toy MC experiments.

Summary

ARGO-130 data taken from July 2006 to February 2007 have been analysed in order to observe the Moon shadow on cosmic rays. With this preliminary set of data, the Moon shadow is obtained with a significance of $\sim$10 standard deviations selecting the events with a number of fired pads > 500.

The effects causing a shift of $\sim 0.25°$ of the shadow with respect to the expected position are currently under investigations.

Studying the shadow width along the North-South axis, where the magnetic deflection is negligible, we obtained for the detector angular resolution a value of $\sigma = 0.51°$, in excellent agreement with Monte Carlo expectations.

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