Observation of TeV cosmic ray anisotropy by the ARGO-YBJ experiment

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***Abstract*. The ARGO-YBJ experiment is a full coverage Extensive Air Shower detector. It has been successfully operated since June 2006 at 4300 m a.s.l. in Tibet, China. The two-dimensional large scale anisotropy of cosmic-ray intensity is observed with an amplitude of about 0.1%, and the amplitude increases when the energy goes from 0.7 TeV to 3.9 TeV. The "Tail-in" and "Loss-cone" structures and the excess in the Cygnus region are observed.**

***Keywords*: Cosmic-ray, anisotropy, cosmic-ray sources**

I. Introduction

Cosmic rays (CRs) at TeV energy are usually considered of Galactic origin. They badly lose directional information and become highly isotropic. During their propagation from the sources to the Earth, they undergo complex processes, such as the deflection by the large scale magnetic field (MF) [4] and the interaction with background photons and the interstellar medium.

Nevertheless, the anisotropy of CRs is still possible for many reasons. Firstly, the local MF configuration is a possible cause. The heliosphere is suggested to be responsible for the "Tail-in" excess and the local interstellar MF for the "Loss-cone" deficit [6]. However, it is argued that the observation of Multi-TeV anisotropy does not favour this interpretation, as the heliosphere cannot influence CRs with energy larger than 10 TeV [11], [15]. Secondly, the diffusion of CRs in the Galaxy can also produce anisotropy, as pointed out by Candia J. et al. [7]. In their diffusion model, the amplitude of anisotropy is larger at higher energy due to the increase of the diffusion coefficient. The discrete distribution of CRs sources is another cause, as it can be seen in the article by Erlykin A.D. et al [8]. In addition to these three cases, the relative motion of the observer to the CRs plasma will introduce a modulation named Compton-Getting effect [9]. But the result of Tibet ASγ has ruled out the relative motion between the solar system and the Galactic CRs [11]. In short, the detailed measurement of the Galactic CRs anisotropy is an essential tool to get information on the origin and the propagation of cosmic rays and on the structure of the Galactic magnetic field.

Several experiments have reported a one-dimensional large scale anisotropy with the magnitude of about 0.1% [10]. Recently, two-dimensional measurements became possible thanks to the larger statistics and the advantage of the wide instrument field of view [5], [10], [11]. In the past, two large scale anisotropic structures have been studied. The excess region was named "Tail-in" and the deficit region was named "Loss-cone" [6]. The new excess around the Cygnus region has also been observed not long ago [11]. In this work, we present the observation of these three regions and the one-dimensional modulation variation as a function of the energy.

II. The ARGO-YBJ Detector

The ARGO-YBJ experiment is located at YangBaJing (Tibet, China, lat. 30.11°N, long. 90.53°E, 4300 m a.s.l.). It is a full coverage cosmic ray air shower array, with large field of view ($\sim$2 sr), high duty cycle ($>$90%) and low energy threshold (few hundred GeV for photons).

The detector is made up of a single layer of Resistive Plate Chambers (RPCs). Each RPC is read out by using 10 PADs (55.6×61.8 cm^2), and each PAD is further divided into 8 strips (6.75×61.80 cm^2). 12 RPCs (2.850×1.225 m^2) make up one cluster (5.7 x 7.6 m^2). 130 clusters fully cover the central area like a carpet ($\sim74\times78$ m^2), which is surrounded by 23 guard ring clusters. The sensitive area of the detector is $\sim$ 6600 m^2 [1].

In shower mode operation, ARGO-YBJ records events with a trigger multiplicity of 20 or more PADs fired in the central 130 clusters. The shower direction is reconstructed by using the time information of the fired PADs, while the shower core position is determined by using the position of the fired PADs [2]. The total number of fired PADs is correlated with the primary CR energy.

III. Data Selection and Analysis

The data used in this analysis have been collected in the whole year 2008. The reconstructed events are selected with zenith angle $<$45°. Usual quality cuts on χ^2 conical fit have been applied to assure the quality of the directional reconstruction; 6.5 x10^{10} events survived the selection criteria.

A global fitting method which incorporates the All-Distance Equi-Zenith Angle method for background estimation is used in the analysis [3].

Lying on an almost horizontal plane, the ARGO-YBJ detector has an almost azimuth-independent efficiency as a function of the zenith angle. So we used the equi-zenith angle method. In brief, shower events collected simultaneously in the same zenith angle belt can be used to build the "off-source windows" and to estimate the background for a candidate point source located in the same zenith range. This method can eliminate various detecting effects caused by instrumental and environmental variations, such as changes in pressure and temperature which are not governable and can introduce systematic errors in the measurement. The celestial sky from 0° to 360° in R.A. and from -15° to 75° in Dec. is binned into cells with a bin size of 2° in both R.A. and Declination. In the local coordinates, the zenith angle θ ranging from 0° to 45° is binned with a step size of 1°, while the azimuth angle ϕ is binned by using a zenith angle dependent bin width (1°/sin(θ)). For every local sidereal time (LST) bin (8min) m, a (n, l) cell in the (θ,ϕ) space is mapped onto a celestial cell (α_i,δ_j), i.e. R.A. bin i and Dec. bin j, through two discrete coordinate transformation functions $\imath(m, n, l)$ and $\jmath(m, n, l)$. Therefore, at a certain LST bin m, the number of events accumulated in the zenith angle bin n and azimuth angle bin l is directly related to the CR intensity $I(i, j)$ in the cell (i, j) of the celestial sky. Being $N_{OBS}(m, n, l)$ the number of observed events after azimuth angle correction, and $I(i, j)$ the relative intensity of CRs, the equi-zenith angle condition leads to the following χ^2 function:

$$\chi^2 = \sum_{m,n,l} \frac{\left[\frac{N_{OBS}(m,n,l)}{I(i,j)} - \frac{\sum_{l' \neq l}[N_{OBS}(m,n,l')/I(i',j')]}{\sum_{l' \neq l} 1}\right]^2}{\frac{N_{OBS}(m,n,l)}{I^2(i,j)} + \frac{\sum_{l' \neq l}[N_{OBS}(m,n,l')/I^2(i',j')]}{\left(\sum_{l' \neq l} 1\right)^2}}$$

Here, (i, j) is mapped from (m, n, l) by the above-mentioned transformation functions. $I(i, j)$ can be calculated by minimizing this χ^2 function. The details of this method can be found in [3].

IV. Monte Carlo Simulation

To estimate the median energy for the data used in this analysis, the proton air shower events were generated by the CORSIKA code v. 6.200[16] with energy ranging from 20 GeV to 100 TeV according to a power-law energy spectrum with differential spectral index -2.71. The hadronic interactions at high energies are treated with the QGSJET-01C model, while low energy interactions are treated with GHEISHA. 2×10^8 events were sampled with zenith angle ranging from 0° to 70°. A GEANT4 based detector simulation code named G4ARGO is used [17]. This detector simulation code uses the same configuration as the ARGO-YBJ detector, including the geometry set, the material of the detectors and the electronics noise. The core positions were sampled in a 500 × 500 m^2 area. The events have been reconstructed with the same procedure used for data reconstruction. The median energy of protons (signed as Ep) corresponding to different fired PADs ranges is obtained by applying the same cuts used for the data.

V. Results and Conclusions

Fig.1 shows the large scale of CRs intensity anisotropy for data taken in 2008 with a median energy of 1.1 TeV. Three evident distinct regions, labelled as I, II and III respectively, appear in the map. Region I is a spread excess area called "Tail-in" [6], and it is composed of two small discrete regions: the first one, located around 65° in R.A. and extending from -10° to 30° in Dec., has a peak significance of 20.8σ and a relative intensity larger than 0.1%; the second one, located around 120° in R.A. and extending from -5° to 55° in Dec., has a peak significance of 18.9σ and a relative intensity of about 0.1%. This small region has been observed by Tibet ASγ [11]. Region II is a large deficit area identified as "Loss-cone" [6], located around 200° in R.A. and extending from -10° to 50° in Declination. The excess in Region III, which is close to the Cygnus region, was first found and identified by Tibet ASγ [11].

Two hot spots in Region I at 10 TeV have been previously reported by Milagro in its study on intermediate scale anisotropy [5]; the same intermediate scale structure has been observed at 2 TeV by the ARGO-YBJ detector [12]. By using our analysis method, we can observe anisotropy in all scales, including the intermediate one: the Region I excess is consistent with that observed by Milagro, as far as the intermediate scale is concerned. Besides the conventional possibility related to the Galactic or local magnetic field, further explanations for Region I have been given without agreement: the excess could be related with the Geminga pulsar as a local cosmic-ray source [13] or it could be due to the magnetic mirror effect of CRs from a local source [14].

Thanks to the large statistics, the energy dependence of the CRs anisotropy is studied for three different PAD multiplicity samples of events; the median energy estimated by means of Monte Carlo simulation is 0.7 TeV, 1.5 TeV and 3.9 TeV respectively. As it can be seen in Fig.2, the amplitude of the anisotropy increases with the CRs median energy growing from 0.7 TeV to 3.9 TeV. In Region I two relatively separated sub-structures expand with the increase of the energy, and at 3.9 TeV they merge into a spot whose shape is very similar to the one observed by the Tibet ASγ experiment with a modal energy of 4 TeV [11]. Fig.3 is the one dimensional projection of Fig.2 in the Right Ascension direction. A second-order cosine harmonics is used to describe this one-dimensional modulation:

$$1 + A_1 cos(2\pi(x - \phi_1)/360) + A_2 cos(2\pi(x - \phi_2)/180)$$

The first order amplitude is found to be 0.04%, 0.07%, 0.1% for the median energy samples of 0.7 TeV, 1.5 TeV, 3.9 TeV respectively. This result is consistent with the results summarized by Guillian [10] obtained by previous experiments and it agrees with diffusion model predicting larger amplitude for higher energy due to the increase of the diffusion coefficient [7].

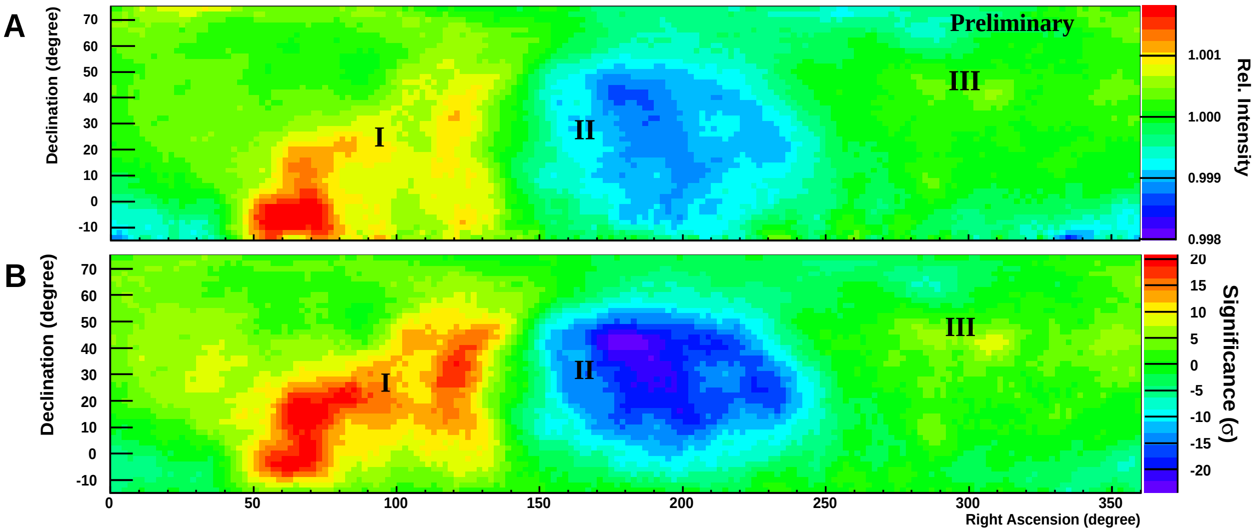

Fig. 1: (A) The large scale of CRs relative intensity anisotropy map obtained by using the data collected in the whole 2008. The Region labelled as I, II, III are the "Tail-in" structure, the "Loss-cone" structure and the excess around the Cygnus region. The left small area in Region I has a relative intensity larger than 0.1%, while the right small region has a relative intensity of about 0.1%. (B) Significance map corresponding to (A). The smoothing angle is 5° and the color scale on the right shows the significance. The left small area in Region I has a peak significance of 20.8σ, while the right small area has a peak significance of 18.9σ.

In conclusion, ARGO-YBJ has observed a two-dimensional CRs anisotropy with amplitude increasing whit the energy going from 0.7 TeV to 3.9 TeV.

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References

[1] Aielli, G. et al., 2006, NIM A562, 92.
[2] Di Sciascio G., et al., 2007, Proc. 30th ICRC, Merida, Mexico.
[3] M. Amenomori et al. 2005, ApJ, 633:1005-1012.
[4] Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., Ptuskin, V. S. 1990, Astrophysics of Cosmic Rays (Amsterdam: North-Holland).
[5] Abdo, A. A., et al. 2008, PRL, 101,221101.
[6] Nagashima K. et al.,1998, Journal of Geophysical Res.,103, 17429.
[7] Candia J.,Mollerach S., Roulet E., J. 2003, Cosmol. Astropart. Phys., 5, 3.
[8] Erlykin A. D., Wolfendale A. W.,2006, Astroparticle Phys., 25, 183.
[9] A. H. Compton, I. A. Getting, 1935, Phy. Rev. Lett., 47, 817.
[10] Guillian G. et al.,2007, Phys. Rev. D, 75, 6.
[11] Amenomori M. et al., 2006, Science, 314, 439.
[12] Vernetto S. et al., 2009, Proc. 31th ICRC, Lodz, Poland.
[13] M. Salvati, B. Sacco, 2008, A&A 485, 527 (arXiv:0802.2181v2).
[14] L. Drury, F. Aharonian, 2008, Astroparticle Physics 29, 420.
[15] Hall, D.L., et al., 1999, JGR 104, 6737.
[16] D. Heck et al. CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers, Forshungszentrum Karlsruhe, FZKA 6019 (1998) and references therein.
[17] Guo Y.Q. et al., 2009, Proc. 31th ICRC, Lodz, Poland.

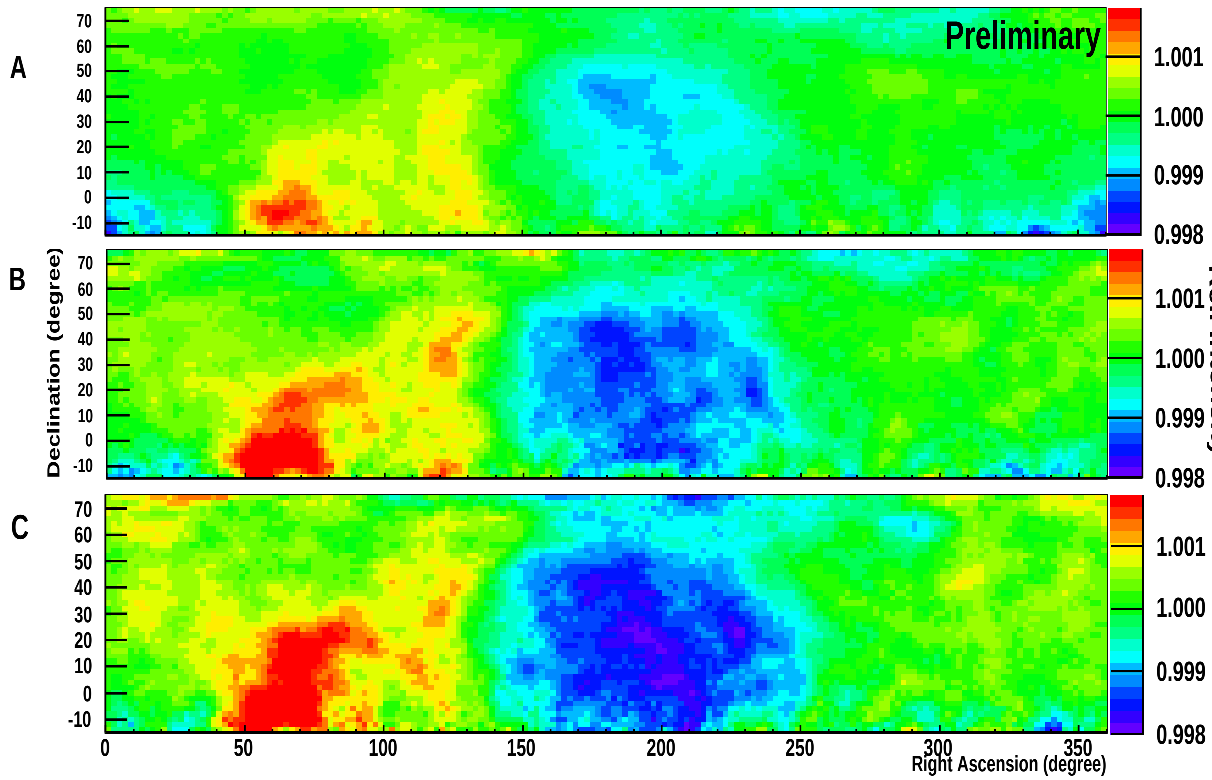

Fig. 2: Two-dimensional CRs intensity maps for representative energies. (A) 0.7 TeV; (B) 1.5TeV; (C) 3.9 TeV;

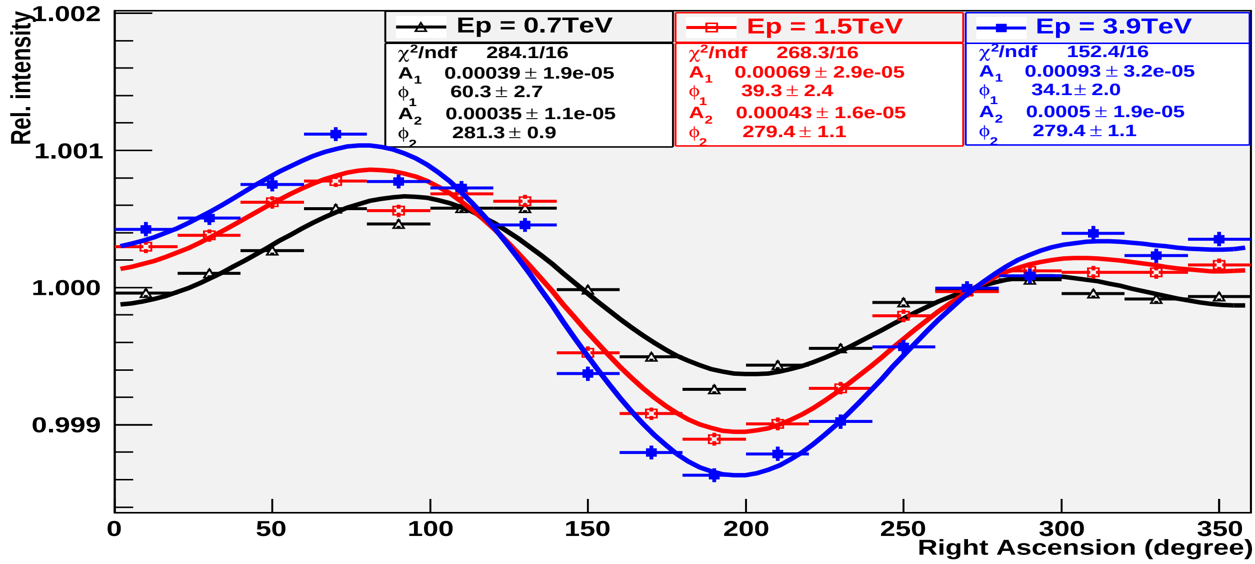

Fig. 3: Sidereal time CRs intensity map for different energy ranges, which is projected from the two-dimensional maps (Fig.2) in Right Ascension. Ep is the median energy of protons estimated by means of Monte Carlo simulations. The three smooth lines are fitted by the second-order cosine harmonics $1 + A_1 cos(2\pi(x - \phi_1)/360) + A_2 cos(2\pi(x - \phi_2)/180)$.