Study on large-scale CR anisotropy with 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. This experiment can survey north sky to study cosmic rays distribution benefited from its high duty cycle and large field of view. We present the observation results of large-scale cosmic ray anisotropy by ARGO-YBJ experiment with the data from 2008 to 2009. We observed that anisotropy intensity amplitude varies with different energy and different time.

Keywords: Anisotropy, ARGO-YBJ, Equi-zenith Method

1 Introduction

Cosmic rays (CRs) at TeV energy are mainly considered as Galactic origin and accelerated by shock waves at supernova remnants. A weak anisotropy of it is observed by many experiments with an amplitude about 0.1% [1][2]. Previously, several experiments[2][3][4][6] have reported a one-dimensional large scale anisotropy as the sidereal time variation at the spinning Earth using underground detectors or ground-based air shower arrays. Recently, benefit from the large statistics and the wide field of view, some experiments [1][2][8] have measured the two-dimensional anisotropy of multi-TeV CRs, and the so-called "tail-in" and "loss-cone" anisotropy features were obtained. The large-scale anisotropy phenomenon may contain information on the nearby cosmic rays source or on the magnetic field structure in our surrounding environment [9]. The long term modulation of the cosmic rays intensity includes both Sun and celestial anisotropy. The celestial anisotropies are due to the Earth motion in the cosmic rays reference system (solar anisotropy: Compton-Getting effect[8]) and to the solar system location inside the Galaxy (siderereal anisotropy).

In this paper, we present the results on the observation of large-scale cosmic ray anisotropy by ARGO-YBJ experiment. In addition, we also present the monthly intensity variation observed at solar time scale and at sidereal time scale. This is the first measurement of anisotropy in a short-time scale within 1 month thanks to the large statistics and stable running of ARGO-YBJ experiment.

2 The ARGO-YBJ Experiment and Data Selection

The Argo-YBJ experiment is an Extensive Air Shower (EAS) array, located at the Yangbajing Cosmic Ray Laboratory (Tibet, P.R.China) at an altitude of 4300 m a.s.l. The detector consists of a single layer of Resistive Plate Chambers (RPCs) operating in streamer mode and has a modular structure, the basic module being the Cluster (5.7 × 7.6 m²), and 12 RPCs (2.850 × 1.225 m²) make up one cluster. The central area like a carpet (about 74 × 78 m²) is fully covered by 130 clusters, which is surrounded by 23 sampling guard ring clusters with a detection area of 6700 m² and about 93% of active area. The detector is connected with two different DAQs corresponding to two operation modes: the shower and the scaler modes. In shower mode, for each event the location and timing of the secondary particles is recorded, allowing the reconstruction of the lateral distribution and the arrival direction with a threshold energy of a few hundreds of GeV. The data used in this analysis was collected by ARGO-YBJ from 2008 January to 2009 December. The events selected condition based on the following criteria:

1. Reconstructed zenith angle ≤45°deg;
2. Number of hits of event ≥40;
3. \(\chi^2\) of events reconstructed ≤80.

These criteria guarantee the quality of the events.
3 Analysis Method

Equi-zenith angle method has some advantages for analysis the CR work, because it can eliminate various detecting effects caused by instrumental and environmental variations, such as changes in pressure and temperature. So we use \( \chi^2 \) iteration equation based on equi-zenith angle method[3][1]. The detectors are toward to the same sky region at the same Local Sidereal Time(LST), we can connect the sky points in the horizontal coordinate with that in the equatorial coordinate. We denote \( I_{i,j} \) as the relative intensity of sky cell (\( \alpha_i \)--Right Ascension, \( \delta_j \)--Declination).

We take \( N(\alpha_i, \delta_j) \) as the number of CRs from direction \( (\alpha_i, \delta_j) \), and \( N_0(\alpha_i, \delta_j) \) as the background events from same direction which are estimated by averaged the different azimuth directions in the same zenith angle.

\[
I_{i,j} \equiv \frac{N(\alpha_i, \delta_j)}{N_0(\alpha_i, \delta_j)}
\]

(1)

From general knowledge , we know that \( I_{i,j} \) is very close to unit 1. So we can construct the \( \chi^2 \) function as below :

\[
\chi^2 = \sum_{m,n,l} \frac{N(m, n, l) / I_{i,j}^{(k+1)} - N(m, n, l') / I_{i,j}^{(k)}}{N(m, n, l) / I_{i,j}^{(k+1)} + N(m, n, l') / I_{i,j}^{(k)}}^2
\]

(2)

here \( m, n, l \) correspond to the Local Sidereal Time,Zenith angle, and Azimuth in the horizontal coordinate system respectively. And \( l' \) means other azimuth direction besides \( l \) at the same zenith angle and the same LST . \( k \) and \( k + 1 \) is labeled for the iteration times. After twenty or more times iterating, we can get minimized value of \( \chi^2 \). Then \( I^{(i,j)} \) can be calculated by the solution of this function. Significance \( s \) can be calculated by

\[
s = \frac{I_{i,j}}{\sigma_{I_{i,j}}}
\]

(3)

4 Azimuth Modification

When we construct the \( \chi^2 \) function, there is a precondition in theory that CRs azimuth distribution is uniform or it is very close to uniform. But actually it is a different case for experiment. Fig1 shows CRs events azimuth distribution recorded by ARGO-YBJ experiment, obviously it is a non-uniform distribution. Our study result shows that such a distribution is very stable during a certain long time. There are two reasons of this effect, one is array of detectors are asymmetric and another reason is the impact of geomagnetic field. Both of them are long-lasting and stable, so we can make correction for these effects with the performance of long term data. Therefore we modify the azimuth distribution by different zenith angle band before the Equi-Zenith method appliance.

5 Results

5.1 Sidereal Anisotropy

The rotation of the Earth enables a ground-based experiment to scan the sky in right ascension direction therefore allowing the detection of a modulation in the intensity of the primary cosmic rays with a period of one sidereal day. Fig2(A) shows the significance skymap after smoothing within 5° solid circle angle in equatorial coordinates. There are obvious a large deficit area in the map named "loss-cone" and a high rise area called "tail-in" , also the Cygnus region has 13σ far beyond the background level. Fig2(B) shows the relative intensity varies at Right Ascension direction, which can be described by the first and second-order cosine harmonics function like

\[
A_1 \cos \phi + A_2 \cos 2\phi
\]

The fit amplitudes and phase are \( A_1 = 6.8 \times 10^{-4}, A_2 = 4.9 \times 10^{-4} \) and \( \phi_1 = 39.1°, \phi_2 = 281° \). These results agree with previous experiments (such as Tibet AS sample experiment, located at the same site as ARGO-YBJ).

5.2 Energy Dependence

The intensity amplitude of anisotropy is a measurable vector which connect with the changes in the external environment such as Interplanetary Magnetic Field. We have searched for energy dependent effects using our data. We divide the events into six groups as the number of hits recorded by the detectors (\( N_{hits} \equiv 40 \sim 60, 60 \sim 100, 100 \sim 160, 160 \sim 300, 300 \sim 700, 700 \sim \)). The median energies of the six group events are estimated by full Monte-Carlo simulation, they are 0.9TeV, 1.52TeV, 2.41TeV, 3.58TeV, 7.17TeV and 18.31TeV respectively. Fig3 shows the intensity skymaps for six \( N_{hits} \) bins. The pictures From top to bottom present low-\( N_{hits} \) to high-\( N_{hits} \) bins. For each picture, we can fit the function of one-dimension projection at right ascension. Fig4 shows
Figure 2: (A) Two-dimension Significance map distribution of CRs by ARGO-YBJ experiment with the data collected from January 2008 to December 2009. Smoothing angle is 5°. x-axis is Right Ascension and y-axis is Declination both in the unit degree and the different colors represent different significance value marked on the right of figure. (B) Distribution of relative intensity as a function of Right Ascension. The smooth fitting line is the second-order cosine harmonics function $1 + P_0 \cos(2\pi(x - P_2)/360) + P_1 \cos(2\pi(x - P_3)/180)$.

Figure 3: CRs intensity skymaps for six $N_{hits}$ bins. The pictures from top to bottom present low-$N_{hits}$ to high-$N_{hits}$ bins.

that the first order amplitude variation of anisotropy as a function of CR’s energies. The amplitude of anisotropy increases at sub-TeV region and it tends to decrease in the higher energy region. It provides an helpful message to understand the origin of anisotropy.

5.3 Monthly Variation and Solar Anisotropy

In order to better understand the possible nature of the anisotropy, we have checked the monthly variation of CRs intensity distribution in the equatorial system (Fig.5). We know that if the intensity depends on the direction relative to the Sun, a modulation with a period of one solar day is recorded. So we also have checked their distribution in the solar-time scale (Fig.6). So far, it is the first time giving the monthly observation of anisotropy by ground experiment. We tend to understand the effect from different solar magnetic field. Fig.6 shows that correlation of sidereal time anisotropy and solar time anisotropy with monthly intensity amplitude fitted by first harmonic function. In our analysis, within such a period of time (one month), they are largely reflect the same thing, and we have to develop new methods to separate the different anisotropy, or have long enough detection period so that it consist in both whole cycles of solar time and sidereal time. And the detailed study is undergoing.
6 Conclusion and Discussion

The measurement of large scale anisotropies is discussed at this work. We have detected the large-scale anisotropy of CRs by ARGO-YBJ experiment with two years data from 2008 to 2009. We report the anisotropy energy dependence. The profile of intensity variation with energy can be used to understand the original of anisotropy phenomenon. In addition, we also report the monthly variation of anisotropy at sidereal time frequency and solar time frequency. It is first monthly detection by ground-based experiment. In our analysis, variation of Solar time anisotropy and sidereal time anisotropy is mixed together so that we can not identified Compton-Getting effect from it, we need more efficient way to separate them each other. And more interesting study works are undergoing.

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