Galactic Cosmic-Ray Anisotropy in the Northern Hemisphere from the ARGO-YBJ Experiment during 2008-2012

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GALACTIC COSMIC-RAY ANISOTROPY IN THE NORTHERN HEMISPHERE FROM THE ARGO-YBJ EXPERIMENT DURING 2008–2012


(The ARGO-YBJ Collaboration)

ABSTRACT

This paper reports on the observation of the sidereal large-scale anisotropy of cosmic rays using data collected by the ARGO-YBJ experiment over 5 years (2008–2012). This analysis extends previous work limited to the period from 2008 January to 2009 December, near the minimum of solar activity between cycles 23 and 24. With the new data sample the period of solar cycle 24 from near minimum to maximum is investigated. A new method is used to improve the energy reconstruction, allowing us to cover a much wider energy range, from 4 to 520 TeV. Below 100 TeV, the anisotropy is dominated by two wide regions, the so-called "tail-in" and "loss-cone" features. At higher energies, a dramatic change of the morphology is confirmed. The yearly time dependence of the anisotropy is investigated. Finally, no noticeable variation of cosmic-ray anisotropy with solar activity is observed for a median energy of 7 TeV.

Keywords: astroparticle physics - cosmic rays

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1. INTRODUCTION

In the past decades, the sidereal directional variation of the Galactic cosmic-ray intensity, which we refer to as the anisotropy, was observed by many detectors across a wide energy range from $60 \text{ GeV}$ to $8 \text{ EeV}$. The morphology of anisotropy and the corresponding amplitude are energy-dependent. The anisotropy implies important information about the magnetic structure of the heliosphere, the local interstellar space surrounding the heliosphere, and large portions of the Galaxy through which cosmic rays propagate to the Earth. The study of anisotropy can shed new light on the origin and propagation of cosmic rays.

Below $100 \text{ TeV}$, two large-scale features recognized as "tail-in" and "loss-cone" features in two dimensional (2D) maps are observed with very high significance both in the northern hemisphere (Amenomori et al. 2006; Bartoli et al. 2015a) and southern hemisphere (Aartsen et al. 2016). According to the ARGO-YBJ observations at energies from $1 \text{ TeV}$ to $30 \text{ TeV}$, the amplitude of anisotropy increases with energy, reaching a maximum at around $10 \text{ TeV}$, while the angular phase is approximately stable (Bartoli et al. 2015a). Different models have been proposed to explain the origin of the anisotropy, concerning different aspects of cosmic-ray physics, from the sources of cosmic rays to the propagation to the Earth. Some models consider the anisotropy due to the spatial distribution of cosmic-ray sources, as the presence of a nearby strong source (Erlykin & Wolfendale 2006; Liu et al. 2017). Other interpretations concern the structure of the Galactic (Qu et al. 2012), local interstellar (Schwadron et al. 2014) and interplanetary magnetic fields (Nagashima et al. 1998). Besides the large-scale anisotropy (LSA), some works focusing on medium scale anisotropy were also reported by Milagro (Aab et al. 2008) and ARGO-YBJ (Bartoli et al. 2013b).

No variations with time are expected if the LSA is produced by a nearby source or due to the interstellar magnetic field, while a significant heliospheric influence would show time variation in association with the 11-year solar cycle. Several long term experiments allow time-dependent studies of the LSA; however, contradictory results were obtained. In the northern hemisphere, Milagro reported a steady increase in the amplitude of the "loss-cone" at $6 \text{ TeV}$ over a seven-year time period ($2000-2007$) as the solar activity varied from near maximum to minimum (Aab et al. 2009). If this observation is true, it will be a challenge to find a consistent explanation of the observed anisotropy and the corresponding time evolution. However, no significant time variations were observed by Tibet AS$\gamma$ at $4.4$, $6.2$, and $11 \text{ TeV}$ over a period that overlapped with the Milagro observation time, from 1999 to 2008 (Amenomori et al. 2012). In the southern hemisphere, no time dependence was observed by IceCube at energies above $13 \text{ TeV}$ over a six-year time period (2009-2015) as the solar activity varied from near minimum to maximum (Aartsen et al. 2016).

As the energy increases above $100 \text{ TeV}$, a major change in the morphology of the anisotropy is observed by several experiments. For such high energy cosmic rays, the influence of the magnetic field within the heliosphere on the cosmic-ray anisotropy is expected negligible. Therefore, the morphology should be time independent. The EAS-TOP collaboration reported a detection of a new anisotropy pattern at $370 \text{ TeV}$ with a limited significance (Agrilietta et al. 2009) for the first time. Around $400 \text{ TeV}$, IceCube found that the structure of the anisotropy is mostly characterized by a wide relative deficit at a right ascension of $30^\circ -120^\circ$ (Abbasi et al. 2012). With the accumulation of six years of data, the IceCube collaboration found that the change in the morphology starts from about $100 \text{ TeV}$ and the amplitude of the deficit increases with energy up to at least $5 \text{ PeV}$ (Aartsen et al. 2016). Recently, the Tibet AS$\gamma$ collaboration improved their analysis with detecting LSA at $300 \text{ TeV}$ which is in close agreement with IceCube's results (Amenomori et al. 2017). The study of LSA at energies above $100 \text{ TeV}$ is helpful to understand the origin and propagation of Galactic cosmic rays. The observed phase of the excess region is different from that at $100 \text{ TeV}$, and $5 \text{ PeV}$. The direction of the anisotropy indicates an extragalactic origin for these ultrahigh energy particles.

Based on the first two years of data (2008 and 2009), the ARGO-YBJ collaboration have reported an energy dependence of the LSA at energies from $1 \text{ TeV}$ to $30 \text{ TeV}$ (Bartoli et al. 2015a). In this paper, we present a new analysis with five years data of the ARGO-YBJ experiment collected from 2008 to 2012. During this period, the solar activity varied from near minimum to maximum. Therefore, the time dependence of the anisotropy is analyzed to address the contradiction between Milagro and Tibet AS$\gamma$ data. Here, we also adopt an improved energy estimation to extend the maximum energy to above $100 \text{ TeV}$, for which few results have been reported.

2. DATA AND ANALYSIS METHODS

2.1. The ARGO-YBJ experiment and data

The ARGO-YBJ experiment, located at the Yangbajing Cosmic Ray Laboratory (Tibet, China, 30.11 N, 90.53 E, altitude of 4300 m a.s.l.), is mainly devoted to $\gamma$-ray astronomy (Bartoli et al. 2013a, 2014, 2016) and cosmic-ray physics (Bartoli et al. 2012, 2015b). The detector consists of a carpet ($\sim74 \times 78 \text{ m}^2$) of resistive plate chambers (RPCs) with $\sim93\%$ of active area, surrounded by a partially instrumented area ($\sim20\%$) up to $\sim100 \times 110 \text{ m}^2$. Each RPC is read out via 80 strips ($6.75 \text{ cm} \times 61.8 \text{ cm}$), logically organized in 10 pads ($55.6 \text{ cm} \times 61.8 \text{ cm}$). The pad is the basic unit for timing and trigger purposes. Each pad can count the number of particles, up to 8. More details of the detector and its performance can be found in Aielli et al. (2006, 2009). The ARGO-YBJ experiment in its final configuration started taking data in 2007 November and stopped in 2013 January. The ARGO-YBJ detector is operated by requiring the coincidence of at least 20 fired pads within $420 \text{ ns}$ on the central carpet detector. The trigger rate is $3.5 \text{ kHz}$ with a dead time of $4\%$. Through the whole operation period, the average duty-cycle is higher than $86\%$. The data collected from January 2008 to December 2012 are used in this analysis.

According to the data selection used in the analysis carried out in Bartoli et al. (2015a), only the data collected in days with average temperature inside the ARGO Hall ($T_{\text{avg}} > 10^\circ \text{C}$) are used. This selection removed 35, 78, 130, and 87 days of data during the years 2008, 2010, 2011, and 2012, respectively.

2.2. Energy reconstruction and data selection
The cosmic-ray energy has been estimated by a Monte Carlo (MC) simulation. Five groups of dominant component elements, H, He, CNO, Mg-Si, and Fe, are generated according to Gaisser et al. (2013). The interaction of cosmic rays in the atmosphere is simulated by CORSIKA code v.7.4005 (Heck et al. 1998), with the hadronic interaction model GHEISHA at lower energy and QGSJET-II at higher energy. About $4 \times 10^{10}$ events are sampled with zenith angle distributed from $0^\circ$ to $60^\circ$ and energy distributed from 10 GeV to 10 PeV. The detector response is simulated with the G4argo code (Guo et al. 2010) based on GEANT-4.

Generally, the primary energy of an event is positively correlated with the number of fired detectors. The number of fired pads was solely adopted to infer the primary energy in our previous analysis (Bartoli et al. 2013b, 2015c). In fact, for events with same number of fired strips (or pads), the true primary energy $E_{\text{true}}$ is also related to the incident zenith angle. In this analysis, the primary energy is first reconstructed based on the number of fired strips $N_{\text{str}}$. The left panel of Figure 1 shows the average relation between $N_{\text{str}}$ and $E_{\text{true}}$. The reconstructed energy at this step is denoted as $E'_{\text{rec}}$. Second, the reconstructed energy is further corrected based on the zenith angle. The middle panel of Figure 1 shows the difference between $E'_{\text{rec}}$ and $E_{\text{true}}$ as a function of zenith angle. The final reconstructed energy is denoted as $E_{\text{rec}}$. The right panel of Figure 1 shows the relation between $E_{\text{true}}$ and $E_{\text{rec}}$, which is a good linear relation.

For the analysis presented in this paper, events are selected according to the following cuts: (1) more than 20 fired strips in the central carpet ($N_{\text{str}} \geq 20$), (2) zenith angle less than 50°, (3) core location less than 100 m from the carpet center, and (4) reconstructed energy $E_{\text{rec}} \geq 10^{3.5}$ GeV. Finally, about $3.03 \times 10^{10}$ events survived. The median energy is about 7 TeV.

### 2.3. Analysis methods

The same analysis methods as used in Bartoli et al. (2015c) are adopted in this work. The background map is estimated via the equi-zenith angle method based on an iterative procedure. More details about this approach can be found elsewhere (Amenomori et al. 2005, Li et al. 2012). This method can reduce the influence of instrumental and environmental variations. With this approach, the 2D LSA anisotropy can be determined. The 2D sky in celestial coordinates is divided into a grid of $2^\circ \times 2^\circ$ pixels. The relative intensity in the $(i, j)$th pixel is defined as

$$ I_{i,j} = \frac{N_{i,j}}{B_{i,j}} $$

where $N_{i,j}$ is the number of detected events, and $B_{i,j}$ is the estimate of isotropic background events. Due to the Earth's rotation, a ground-based array as ARGO-YBJ is sensitive to the anisotropy in right ascension. The exposure at different declination bands has been estimated with good precision enough to measure the cosmic ray energy spectrum. However, a better accuracy is likely needed to measure a dipolar signal along the declination. Thus this analysis is sensitive to anisotropy in right ascension and the changes in relative intensity across declination belts.

To estimate the amplitude and phase of the anisotropy, a one-dimensional (1D) anisotropy is calculated as the profile of relative intensity in right ascension. The 1D profile of the anisotropy is fitted by a first-order harmonic function in the form of

$$ I = 1 + A \cos(\alpha - \phi), $$

where $A$ is the amplitude of the anisotropy and $\phi$ is the corresponding phase.

### 3. Results

#### 3.1. Time dependence of the sidereal anisotropy

Figure 2 shows the yearly relative intensity of the LSA from 2008 to 2012. The 2D maps are smoothed with an angular radius of 15°. The median energy is about 7 TeV. The "tail-in" and "loss-cone" structures are distinct in the map and almost stable in these years. To check the yearly variation of the anisotropy, the penultimate panel of Figure 2 shows 1D profiles of the sidereal anisotropy for five years. The bin size for the 1D profile is 20° in the direction of right ascension. No substantial or significant variation of the LSA is detected over five years for our total sample with a median energy of 7 TeV. The anti-sidereal anisotropy, shown in the bottom panel of Figure 2, should not have a physical origin but rather could arise due to an interaction between a solar diurnal anisotropy and an annual variation. Such an interaction could also contaminate the sidereal anisotropy. The bottom panel shows a very weak anti-sidereal anisotropy, which therefore implies very little contamination of the sidereal anisotropy by such an interaction.

The Milagro collaboration reported a steady increase in the amplitude of the "loss-cone" at 6 TeV from July 2000 to July 2007, corresponding to the period from maximum to near minimum of solar cycle 23 (Abdo et al. 2009). However, the Tibet AS-γ collaboration reported a stable anisotropy from November 1999 to December 2008 (Amenomori et al. 2012). Located at the northern hemisphere, ARGO-YBJ covers about the same sky region as Milagro and Tibet AS-γ. The energy range of this ARGO-YBJ sample is also very similar to those
of Milagro and Tibet AS$_{\gamma}$. The operation period from 2008 to 2012 covers the period of solar cycle from minimum to near maximum. Therefore, ARGO-YBJ is a very suitable detector to address the conflict between those Milagro and Tibet AS$_{\gamma}$ results.

Table 1 shows the "loss-cone" amplitude observed by ARGO-YBJ along with the statistical and systematic errors. The "loss-cone" amplitude is defined as the difference between the relative intensity at the minimum of a best fit second-order harmonic function and unity. The statistical error is calculated simply by propagating the statistical errors of the parameters in the fit function. The systematic errors are estimated by the fitted amplitude in anti-sidereal time (the last panel of Figure 2). Figure 3 shows the yearly "loss-cone" amplitude observed by ARGO-YBJ during the five years. The error bars represent the sum of statistical and systematic errors. The results of Milagro (Abdo et al. 2009) and Tibet AS$_{\gamma}$ (Amenomori et al. 2013) are also presented here for comparison.

Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Loss-cone amplitude (%)</th>
<th>Stat. error (%)</th>
<th>Syst. error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.172</td>
<td>0.00175</td>
<td>0.0076</td>
</tr>
<tr>
<td>2009</td>
<td>0.137</td>
<td>0.00168</td>
<td>0.0300</td>
</tr>
<tr>
<td>2010</td>
<td>0.158</td>
<td>0.00192</td>
<td>0.0376</td>
</tr>
<tr>
<td>2011</td>
<td>0.142</td>
<td>0.00208</td>
<td>0.0160</td>
</tr>
<tr>
<td>2012</td>
<td>0.149</td>
<td>0.00194</td>
<td>0.0279</td>
</tr>
</tbody>
</table>

Figure 3. Temporal variation of "loss-cone" amplitude of ARGO-YBJ data from January 2008 to December 2012. The error bars represent the sum of systematic and statistical errors. The results of Milagro (Abdo et al. 2009) and Tibet AS$_{\gamma}$ (Amenomori et al. 2013) are also presented here for comparison.

Table 2

<table>
<thead>
<tr>
<th>Energy bin (GeV)</th>
<th>Median energy (TeV)</th>
<th>Number of events ($N$)</th>
<th>Amplitude ($A$)</th>
<th>Phase ($\phi$ (deg))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.50-3.75</td>
<td>4.0</td>
<td>143.0</td>
<td>9.54 ± 0.12</td>
<td>24.7 ± 0.7</td>
</tr>
<tr>
<td>3.75-4.00</td>
<td>7.1</td>
<td>77.4</td>
<td>11.92 ± 0.16</td>
<td>29.9 ± 0.8</td>
</tr>
<tr>
<td>4.00-4.25</td>
<td>12</td>
<td>41.7</td>
<td>11.71 ± 0.22</td>
<td>24.0 ± 1.1</td>
</tr>
<tr>
<td>4.25-4.50</td>
<td>22</td>
<td>21.4</td>
<td>11.17 ± 0.31</td>
<td>22.3 ± 1.6</td>
</tr>
<tr>
<td>4.50-4.75</td>
<td>39</td>
<td>10.1</td>
<td>8.19 ± 0.45</td>
<td>358.9 ± 3.1</td>
</tr>
<tr>
<td>4.75-5.00</td>
<td>71</td>
<td>4.4</td>
<td>4.23 ± 0.67</td>
<td>347.0 ± 9.1</td>
</tr>
<tr>
<td>5.00-5.50</td>
<td>160</td>
<td>2.6</td>
<td>7.81 ± 0.88</td>
<td>251.1 ± 6.5</td>
</tr>
<tr>
<td>≥5.50</td>
<td>520</td>
<td>0.4</td>
<td>9.10 ± 2.29</td>
<td>279.2 ± 14.5</td>
</tr>
</tbody>
</table>
LSA for each energy interval. The maps are smoothed with an angular radius of 30°. The "tail-in" and "loss-cone" features are significant at energies from 4 TeV to 22 TeV. At energies from 39 TeV to 71 TeV, the "tail-in" and "loss-cone" features gradually fade away. At the same time, a new excess feature around the right ascension of 250°-300° gradually appears, replacing the structure of the "loss-cone". At energies above 160 TeV, the "tail-in" and "loss-cone" features completely disappear, and the map is dominated by a new pattern with an excess around the right ascension of 200°-310° and a deficit around 0°-100°. These characteristics are consistent with those observed by the Tibet experiment (Amenomori et al. 2017) in the Northern Hemisphere.

To quantitatively estimate the evolution of the LSA, equation (2) presented in Section 2.3 is used to fit the 1D profiles shown in Figure 4 (middle panels). The chi-square values indicate that, mainly at low energies, the cosmic-ray anisotropy is not well described by a pure dipole, but a simple dipole fit is commonly used to estimate its amplitude and phase. The fitted parameters, i.e., the amplitudes and phases, as a function of energy are shown in Figure 5 and also listed in Table 2. The error bars of the amplitude contain the statistical errors and the systematic errors exhibited by the anti-sidereal 1D profiles of Figure 4 (right panels). As shown the amplitudes are energy dependent with a maximum around 7 TeV, above which the amplitude begins to decrease with the phase gradually shifting. At energies above 100 TeV, a sudden change of the phase is observed and the amplitude also begins to increase. According to the fitting parameters shown in Figure 4, the significance of non-zero amplitude is 8.8σ and 4.0σ at energies of 160 TeV and 520 TeV, respectively, implying that the obtained LSA features are significant. The phases at 160 TeV and 520 TeV are $\alpha = 251.1^\circ \pm 6.5^\circ$ and $\alpha = 279.2^\circ \pm 14.5^\circ$, respectively, which are consistent with Tibet ASγ (Amenomori et al. 2017) and IceCube (Aartsen et al. 2016). The direction of the new excess is very close to the direction of the Galactic Center (268.4° R.A.), hinting that this region is the dominant origin of the cosmic rays. For comparison, the results reported by...
The LSA amplitude in sidereal time. At 160 T eV, the systematic change of the morphology, consistent with the observations reported by IceCube in the southern hemisphere and T-BET AS\textsuperscript{2} in the northern hemisphere, is clearly observed starting from about 50 TeV. The dipole at 160 TeV and 520 TeV is aligned (at $\alpha = 251.1^\circ \pm 6.5^\circ$ and $\alpha = 279.2^\circ \pm 14.5^\circ$, respectively) near the direction of the Galactic Center (268.4$^\circ$, R.A.), suggesting this region as a possible source of cosmic rays.

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The observed results for the anti-sidereal frequency support the reliability of the observed sidereal anisotropy presented in this work.

4. DISCUSSION AND SUMMARY

In this analysis, only events with reconstructed energy above 3 TeV are used. During five years, no significant time dependence of the anisotropy is detected. However, this result does not exclude the possibility of time-dependent variation of the anisotropy at lower energy. According to the estimation of Zhang et al. (2014), the magnetic field within the heliosphere has minor influence on anisotropy above 4 TeV, and the influence will be visible at energies below 1 TeV. According to Figure 5, ARGO-YBJ can also reach the sub-TeV energy band. A study of the behavior of the anisotropy at energies below 3 TeV is deferred to a future publication.

This paper reports on the measurement of the large-scale cosmic-ray anisotropy by the ARGO-YBJ experiment with data collected from January 2008 to December 2012. This analysis extends a previous report limited to the period from 2008 January to 2009 December, near the minimum of solar activity between cycles 23 and 24. In contrast with a previous report by the Milagro experiment, no significant time dependence of the anisotropy is detected for a median energy of 7 TeV during 5 years, when the solar activity changed from near minimum to maximum of solar cycle 24. With an improved energy reconstruction procedure, we extended the energy range investigated by ARGO-YBJ up to 520 TeV. A dramatic change of the morphology, consistent with the observations reported by IceCube in the southern hemisphere and T-bet AS\textsuperscript{2} in the northern hemisphere, is clearly observed starting from about 50 TeV. The dipole at 160 TeV and 520 TeV is aligned (at $\alpha = 251.1^\circ \pm 6.5^\circ$ and $\alpha = 279.2^\circ \pm 14.5^\circ$, respectively) near the direction of the Galactic Center (268.4$^\circ$, R.A.), suggesting this region as a possible source of cosmic rays.