Observation of the cosmic ray large-scale anisotropy with the ARGO-YBJ experiment

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Abstract. This paper reports on the observation of the sidereal large-scale anisotropy of cosmic rays using the ARGO-YBJ data collected from 2008 January to 2012 December. The anisotropy is investigated within a wide 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. The maximum value of the anisotropy is around 7 TeV. No noticeable variation of cosmic-ray anisotropy with solar activity is observed during the 5 years even though the solar activity varied from near minimum to maximum. Above 100 TeV, a dramatic change of the morphology is confirmed. The physical implications of these results are also discussed.

1. Introduction

Cosmic rays are high energy particles, mainly originating outside the solar system. The primary energy spectrum extends over many orders of magnitude from $10^9$ eV up to $10^{20}$ eV, generally following a steeply falling power-law spectrum. A prominent feature is the change in the spectral index around 4 PeV, known as the cosmic ray knee, which was discovered 60 years ago [1]. Recent measurement has shown that the knee may be attributed to the elements heavier than hydrogen and helium [2]. It is believed that the cosmic rays with energies around and below the knee region are the products of energetic process within Galactic objects. The knee feature may be caused by the acceleration limit within the acceleration sites. The shocks of supernova remnants have been suspected to be the main acceleration sites for a long time. The population of young massive stars has been also suggested by [3] as the possible main origin.

Recently, important progresses have been achieved by several spaced-based detectors. A nearly universal hardening of the spectra near the magnetic rigidity of 200 GV was observed in the spectra of all abundant cosmic ray nuclei [4, 5, 6]. This feature is consistent with the new universal cosmic ray knee around 10 TV revealed by the NUCLEON detector [7]. These results may indicate three source classes for the Galactic cosmic rays as suggested in [8]. To further investigate the origins of cosmic rays, directional information is needed. For such a scenario, the cosmic ray anisotropy will be helpful.

In the past decades, the anisotropy of cosmic ray intensity was observed across a wide energy range from 60 GeV to 8 EeV. The morphology and amplitude are energy dependent. The large-scale anisotropy at energy from sub-TeV to tens of TeV has been detected by many experiments.
Figure 1. Displacement of the Moon shadow from the apparent center in the North-South (upper) and East-West (middle) direction. Lower panel is the ratio of the observed deficit count to the expected one. The solid line in each panel is the fitting result with a constant parameter.

The observed anisotropy map is dominated by two wide regions of excess and deficit, recognized as “tail-in” and “loss-cone” features, respectively. At energy above 100 TeV, a major change in the morphology was observed by EAS-TOP [10], IceCube [11], and Tibet ASγ [12].

The ARGO-YBJ experiment is a full-coverage extensive air shower array, sensitive to cosmic rays with the energy threshold of a few hundred GeV. A specific analysis on medium-scale anisotropy using ARGO-YBJ data has been reported in [13]. Several hot spots were observed. Based on the first 2 years of ARGO-YBJ data (2008 and 2009), an energy dependence of the large-scale anisotropy at energies from 1 to 30 TeV was reported in [14]. Very recently, a new analysis with the 5 years of ARGO-YBJ data collected from 2008 to 2012 was implemented [9]. A new method was used to improve the energy reconstruction, allowing to cover a much wider energy range, from 4 to 520 TeV. In this paper, we will review the data analysis and the results.

2. The ARGO-YBJ experiment and the data

The ARGO-YBJ experiment, a collaboration among Chinese and Italian institutions, is a full coverage extensive air shower detector with RPCs at Yangbajing (Tibet, China, 4300 m a.s.l.). It is mainly devoted to γ-ray astronomy [15, 16, 17] and cosmic ray physics [18, 2]. The full detector was in stable data taking from November 2007 to January 2013. The trigger rate is ∼3.5 kHz with a dead time of 4% and the average duty cycle is higher than 86%.

To monitor the long-term stability of the detector performance as far as the pointing accuracy and the angular resolution, both the position of the Moon shadow, separately along R.A. and DEC. projections, and the amount of shadow deficit events were monitored monthly as shown in Figure 1. The position of the Moon shadow turned out to be stable at level of 0.1° and the angular resolution was stable at level of 10% [19].

Figure 2 shows the daily average temperature < T_in > inside the ARGO Hall during the period from 2008 to 2012. The average temperature was lower than 10°C in the winters of 2010, 2011 and 2012, while this feature was absent in 2009. To further check the data, the stability of the azimuth distribution within one day during the winter periods when < T_in > < 10°C was investigated. A tiny variation (∼0.5%) of the azimuth distribution was observed, which was correlated with the variation of temperature. Such a variation was not observed during the summer periods when < T_in > > 10°C. According to Figure 1, the influence on the Moon shadow, as well as on the γ-ray data, can be ignored. However, the analysis of large-scale anisotropy is much sensitive to the stability of the azimuth distribution. Therefore, only the data collected in days with < T_in > > 10°C were used in this work. This criterion removed 35, 78, 130, and 87
Figure 2. The daily average temperature inside the ARGO Hall during the period from 2008 to 2012. The error bar shows the variation range of the temperature within one day.

Figure 3. Relative intensity of LSA from 2008 to 2012. The median energy is 7 TeV. The maps are smoothed with 15° angular radius.

days of data during the years of 2008, 2010, 2011, and 2012, respectively.

Generally, the primary energy of an event is positively correlated with the number of fired pick-up electrodes of the detector. The number of fired electrodes was solely adopted to infer the primary energy in our previous analysis [14]. In this work, a new method was used to improve the energy reconstruction. Both the number of fired electrodes and the incident zenith angle were used to reconstruct the primary energy. More details about this reconstruction can be found in [9]. The events with reconstructed energy $\geq 10^{2.5}$ GeV, about $3.03 \times 10^{10}$ events, were used in this analysis. The median energy is 7 TeV.

3. Results

In this work, the same analysis method as that used in [14] was adopted. The background map was estimated via the equi-zenith angle method based on an iterative procedure. With this approach, the 2D large-scale anisotropy can be determined.

Figure 3 shows the yearly relative intensity of the large-scale anisotropy from 2008 to 2012. The “tail-in” and “loss-cone” structures are distinct and almost stable during these
years. It is worth to note that the Milagro collaboration reported a steady increase in the amplitude of the “loss-cone” which was coincident with the decreasing of the solar activity [20], however, this result conflicted with the Tibet AS\(\gamma\) result [21]. Figure 4 shows the yearly “loss-cone” amplitude observed by ARGO-YBJ. The error bars represent the sum of statistical and systematic errors. The systematic error was estimated using the anti-sidereal anisotropy. The “loss-cone” amplitude was constant within errors. No significant time dependence was observed even though the solar activity varied from near minimum to maximum as shown in Figure 4. For comparison, Figure 4 also shows the results of Milagro and Tibet AS\(\gamma\). The ARGO-YBJ result is mostly consistent with the same constant value as Tibet AS\(\gamma\).

Figure 5 shows the anisotropy at eight energy intervals from 4.0 TeV to 520 TeV. 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°. To quantitatively estimate the evolution of the anisotropy, the 1D profiles of the anisotropy were fitted by a first-order harmonic function, as shown in Figure 5. The fitted parameters, i.e., the amplitudes and phases, as a function of energy are shown in Figure 6. Combining the current result and the previous one [14], the energy dependence of the anisotropy is more evident. The amplitude increases with energy, with a maximum intensity 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. For comparison, the results reported by other detectors are also shown in Figure 6. The results obtained in this work generally agree with others.

4. Discussion and summary
According to current results, the morphology and amplitude variation trend of anisotropy below 100 TeV is very different from that above 100 TeV, implying different origins. This may be consistent with recent progress on the cosmic ray spectrum, which also indicates that the cosmic ray at energies from 1 TeV to 1 PeV may be a mixture from two different source classes [7, 8]. For the anisotropy below 100 TeV, different models have been proposed to explain the origin, concerning different aspects of cosmic ray physics, from the sources of cosmic rays to the
Figure 5. The 2D maps of relative intensity of large-scale anisotropy (left panels) and 1D projections on R.A. (right panels) for eight energy bins. Each 2D plot is smoothed with a 30° angular radius.

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 [25]. Other interpretations concern the local interstellar magnetic fields [22] and interplanetary magnetic fields [23]. According to the time dependence of the anisotropy achieved in this work, the anisotropy above 3 TeV is not correlated with the solar activity. This indicates that the influence of the magnetic field within the heliosphere is not important, which is consistent with the estimation in [24]. If the anisotropy is caused by the local interstellar magnetic fields [22], the amplitude should monotonously decrease with energy increasing. This may be in principle not consistent with observations that the amplitude increases with energy below 7 TeV and decreases above 7 TeV. One plausible reasonable interpretation may be due to a single nearby strong source [25]. The new universal knee of cosmic ray spectrum around 10 TV [7] is close to the peak energy of the anisotropy. This may indicate that the new spectral feature and the anisotropy are correlated for their origin. For the anisotropy above 100 TeV, the excess region is near the direction of the Galactic center, suggesting this region as a possible source of cosmic rays. The variation trend of amplitude increasing as energy increasing is also consistent with scenario of cosmic ray diffusion.

In summary, this paper reports on the measurement of the large-scale cosmic ray anisotropy
Figure 6. The amplitude (left panel) and phase (right panel) of the first harmonic of the sidereal anisotropy as a function of the cosmic-ray energy measured by ARGO-YBJ and other experiments.

by the ARGO-YBJ experiment with data collected from 2008 January to 2012 December. In contrast with a previous report by the Milagro experiment, no significant correlation with solar activity was detected. 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 Tibet ASγ in the northern hemisphere, was clearly observed starting from about 50 TeV.

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