Observation of the large-scale sidereal anisotropy of the galactic cosmic ray intensity at 300 TeV with the Tibet Air Shower Array

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Abstract: We report on the observation of the large-scale sidereal anisotropy of Galactic Cosmic Rays (GCRs) at median energy of $\sim$300 TeV. With long time and high-stability collection by the Tibet air shower array between October 1995 and February 2010, the data used in this analysis contains 3.1×10^8 air shower events with a median angular resolution of 0.3°. A new anisotropy structure at 300 TeV is revealed, which significantly deviates from the picture of cosmic ray isotropic intensity and is different with previous anisotropy observation at Multi-TeV energy. The dominant feature is an excess region that localized at (α = 271.0°, δ = 22.1°), with a significance of 7.3σ (pre-trial) or 5.4σ (post-trial) and an optimized smoothing of 29°. The maximum relative intensity region with an intensity of $\sim 2.0\times10^{-3}$ is around (α = 255.0° , δ = -13.9°), that is close to the highest excess region observed by IceCube at 400 TeV.

Keywords: cosmic rays, anisotropy, Tibet AS Array

1 Introduction

The arrival direction of Galactic Cosmic Rays (GCRs) is nearly isotropic due to deflections in the Galactic Magnetic Field (GMF). However, observations of ground-based experiments in both the northern and the southern hemispheres show that there exists a slight anisotropy with a relative amplitude in the order of 10^{-4} to 10^{-3} on the overall isotropic background between 10 GeV and several tens of TeV. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

Due to the low flux of cosmic rays in the primary ener-

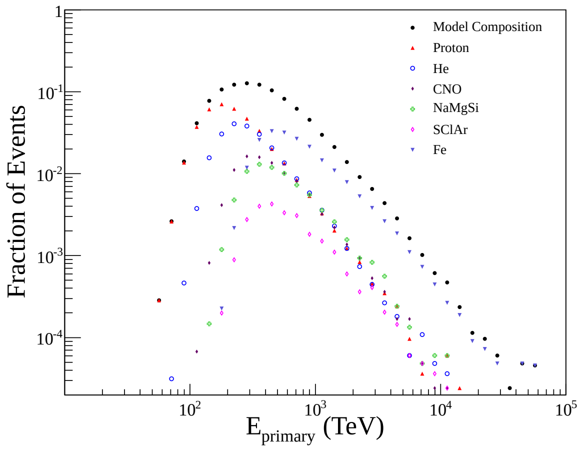

Fig. 1: The normalized number of events simulated by Tibet AS Array vs. primary energy (in TeV), using the HD composition model described in [19]. Fractional contributions of proton, helium, CNO, NaMgSi, SClAr and iron are shown as well.

gy range of several hundreds TeV up to 10 PeV, only few statistically significant anisotropies were reported from ground-based air-shower experiments. EAS-TOP experiment published an anisotropy observation at $E_0 \sim 200$ TeV [11], and later, with more data, reported a sharp increase in the anisotropy for primary energies of ~370 TeV [12]. At higher energy from 0.7 to 6 PeV, no hints for anisotropy in the right ascension distributions were found by the KASCADE experiment [13]. Recently, IceCube experiment reported an observation of an anisotropy at 400 TeV [14] in the southern sky, which was confirmed by Ice-Top experiment [15] later. Furthermore, IceTop found the anisotropy persists to PeV energies [15].

In our previous work [6], the Tibet ASγ collaboration reported an observation for primary energies ~300 TeV to be consistent with cosmic ray isotropic intensity with the data taken by TibetHD array from February 1997 to September 1999 and the Tibet III array from November 1999 to October 2005, including about 1.9×10^8 air shower events in total.

When we were trying to search for 100 TeV γ rays emission [16], we got some hints of 300 TeV cosmic ray anisotropy with the data only collected by Tibet AS array from Oct. 2000 to Dec.2008. Considering that additional 5 years data taking at the Tibet air shower (AS) array is available after our previous work [6], we reanalysed all the data taken by the Tibet AS array.

We present here the large-scale sidereal anisotropy measurement at median energy of ~300 TeV by the Tibet AS array with data collected from October 1995 to February 2010. The data sample with a better energy resolution contains 3.1×10^8 air shower events, which is about 60% higher than used in the previous analysis [6].

2 Experiment and Data Selection

Tibet ASγ experiment is located at Yangbajing in Tibet, China (90.522°E, 30.102°N, 4300 m a.s.l., 606g/cm^2). The effective area of the Tibet AS array has been gradually enlarged in several steps, by adding the same-type plastic scintillation detectors with an area of 0.5 m^2 to the preceding Tibet-I, II and III arrays. In addition, the performance was improved by adding detectors for a more compact array. The Tibet-II array consists of 221 detectors with a 15-m grid covering in total 36900 m^2. It started operation in October 1995 [17]. The current Tibet-III was upgraded to a dense array with 7.5-m grid in 1999 and 2003 [18, 19]. The trigger rates are ~230 Hz and ~1700 Hz for the Tibet-II and III arrays, respectively.

In order to enlarge the data statistics and get a better energy resolution, the data reconstruction and selection are updated. We keep the same form of the data throughout the observation period from October 1995 to February 2010 by reconstructing air showers obtained from the detector configuration of the Tibet-II array completed in 1995 unchanged for the Tibet-III array. So that the full data sample taken by Tibet II and Tibet III array can be used in the present analysis.

The event selection based on the following criteria:

(1) each AS event should fire four or more detectors recording 1.25 or more particles,

(2) the AS core position should be located inside the array,

(3) the zenith angle of the AS event should be less than 45°,

(4) $\sum \rho_{FT}$, which is the sum of the particle number density by all the FT-PMTs, should be larger than 400.

After this data selection and some quality cuts, 3.1×10^8 air shower events are obtained.

In order to estimate the primary energy spectrum of selected event sample, a full Monte Carlo (MC) simulation is performed for the air shower development in the atmosphere by CORSIKA (version 6.204) [20] with QGSJET01c being chosen as the hadronic interaction model and for the detector response by Epics (version 8.65) [21].

Figure 1 shows the simulated primary energy spectrum for the selected event sample assuming the heavy dominant (HD) composition model described in [19]. The median energy of primary particle is ~300 TeV, where 68% of the events are between 250 and 350 TeV. The angular resolution is estimated to be 0.3°. It is worth to point out that the simulated primary energy distribution is similar if we adopt SIBYLL as the hadronic interaction model. In this event sample, the spectrum is dominated by the light primary particles, though the HD composition model is adopted. The fractional contribution of proton is about 38% and of helium is about 22%, while the fractional contribution of iron is about 20%. As shown in Figure 1, the median energy would be 180 TeV if pure proton model is adopted, compared to the median energy of aobut 450 TeV if everything is iron.

3 Analysis

The All-Distance Equi-Zenith Angle Method [22], which was also used in our previous work [6], is applied to the data set, in order to reconstruct a possible large-scale anisotropy. A certain celestial direction at a certain moment of a sidereal day is taken as an on-source window, with its off-sources being all the other directions that belong to the equi-zenith angle belt. This process is repeated over the entire sky and over the whole sidereal day. The idea of this method is that, if the number of events N in a certain direction is scaled down (or up) by the relative intensity I of the direction, then the scaled number of events N=I must be s-

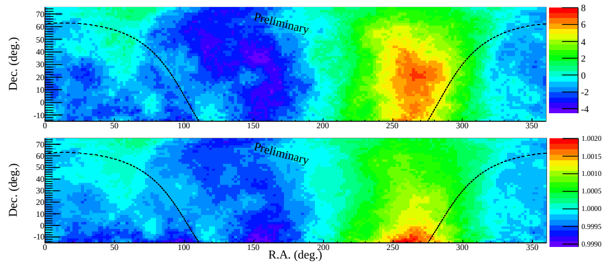

Fig. 2: large scale sidereal anisotropy measurement at 300 TeV by the Tibet AS Array with an optimized smoothing of 29°. The top figure shows the 2D significance map. The bottom figure is the 2D relative intensity map.

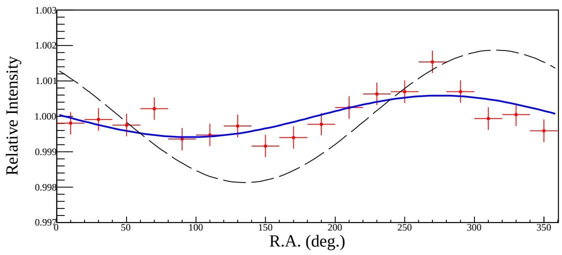

Fig. 3: The one dimensional projection in right ascension α of the two-dimensional cosmic ray map for dec between $-15°$ and 75°. The blue line corresponds to the first and second harmonic fit to the data. The black dashed line is the predicted Galactic CG effect of amplitude $\sim$0.19%

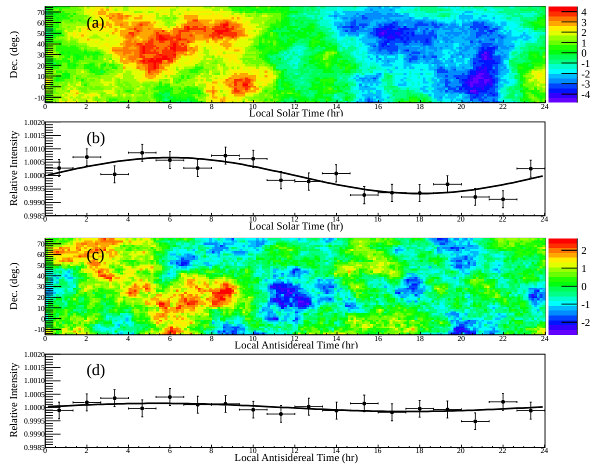

Fig. 4: Solar time and anti-sidereal time anisotropy measurements by Tibet AS Array. The data are shown with statistical uncertainties, and the black line corresponds to the first harmonic fit to the data. (a) shows the 2D relative intensity map with 20° smoothing in the local solar time. (b) shows the one-dimensional projection in the local solar time. (c) shows the 2D significance map with 20 degree smoothing in the local anti-sidereal time. (d) shows the one-dimensional projection in the local anti-sidereal time

tatistically equal to that in any other direction in the equi-zenith angle belt. The χ^2 function is built accordingly, and minimizing the χ^2 function by means of a non-linear least-squares fitting gives the best-fit set of the relative cosmic-ray intensities of all directions in equatorial coordinates. Details about the analysis method are in [22].

In this work, the sky is divided into cells with bin size of 1° in both zenith direction between 0° and 45° and azimuth direction between 0° and 360° , and the sky in equatorial coordinates is divided into cells of $2° \times 2°$ between 0° and 360° in the right ascension (α) and between $-15°$ and 75° in the declination (δ). The smoothing search applied is from 5 to 30 degree.

To quantify the scale of the anisotropy, the one-dimensional (1D) profile of the sidereal anisotropy is created by projecting all the relative intensities in the declination range from $-15°$ to 75° onto the right ascension coordinate. We divide the right ascension into 18 bins. And then the 1D profile of the anisotropy is fitted by a harmonic function in the form of

$$R(\alpha) = 1 + A_1 \cos(\alpha - \phi_1), \quad (1)$$

where $R(\alpha)$ denotes the relative intensity of cosmic ray at right ascension α, A_1 is the amplitude of the 1st harmonic term, ϕ_1 is the phase of the 1st harmonic term, at which the 1st harmonic function reaches its maximum.

4 Result and Discussion

Figure 2 shows the significance and the relative intensity cosmic ray maps with an optimized smoothing of 29°. The anisotropy structure at 300 TeV is revealed, which significantly deviates from the picture of cosmic ray isotropic intensity and is different with previous anisotropy observation at Multi-TeV energy. These maps are dominated by a strong excess. The statistical significance of the excess reaches a maximum of 7.3σ at a location around (α = 271.0°, δ = 22.1°). Since the search for this excess is performed over about 45×180 cells, and across 24 different smoothing radii in total, there is a trials factor of at most 1.944×10^5 that reduces the post-trial significance of the excess to 5.4σ. It should be pointed out that this correction for trials is conservative, because the cells are statistically correlated by the smoothing procedure, which results in a smaller effective number of trials than the maximum and a lower post-trial significance than the real one.

Because the detector acceptance decreases with larger zenith angle, the maximum relative intensity region with an maximum intensity of $\sim 2.0 \times 10^{-3}$ is not located at the most significance excess region, but at a region around (α = 255.0° , δ = $-13.9°$) , that is close to the highest excess region (α = 256.6° , δ = $-25.9°$) observed by IceCube at 400 TeV [14].

Figure 3 shows the projection in right ascension of the cosmic ray relative intensity with statistical uncertainties. In this paper, the correlation among the bins is carefully considered when calculating the statistical errors in each bin and fitting the data by a harmonic function. We want to point out that if the correlation among the bins is not considered, it would results in a smaller statistical error of the fitting parameters. The blue line indicates the fit of eq. 1 to the data. The fitting parameters are shown in Tables 1. Tthe reduced χ^2 values is 31.6/16, which means that the first harmonic function can't describe the 1D projection well.

One of the possible origin is the Compton -Getting (CG) effect [23], caused by the orbital motion of the solar system around the Galactic center. With a Monte Carlo simulation similar to our previous work [6], the predicted CG effect would peak at (α = 315° , δ = 0°) and forms a trough at around (α = 135° , δ = 0°), with a amplitude of $\sim$ 0.19% between $-15°$ and 75° in the declination (δ). The black dashed line in Figure 3 is the predicted Galactic CG effect. The large scale structure observed in this work can't be described in terms of expected CG effect neither in amplitude nor in phase. The basic picture that Galactic cosmic rays is corotated with the local Galactic magnetic environment according to our observation in this work is not changed.

5 Reliability Checks

As a check of the analysis method and the data sample, the same analysis were performed using the solar time frame [24] and the anti-sidereal time frame [25]. Here, the fitting function to the projection in these two time frame is in the form of

$$R(\alpha) = 1 + A\cos[(2\pi(T-\phi)/24] \quad (2)$$

, where the local solar time or local anti-sidereal time T and ϕ are in units of hour and A is the amplitude.

Fig. 4 shows the 2D significance map and the projections of relative intensity for both time frame. Tables 2 and 3 show the results of the fit amplitude and phase along with χ^2/ndf of the fit. The observed solar time anisotropy agrees with the expected Compton-Getting (CG) effect [23] well within statistical error due to the terrestrial orbital motion around the Sun [26]. The observed anti-sidereal time anisotropy show no significant observed amplitude in the anti-sidereal time, which insures the reliability of the anisotropy observed in sidereal time.

Figure	A_{SID} (10^{-4})	ϕ_{SID} (degree)	χ^2/ndf
Fig.3	$5.9 \pm 2.0_{stat.}$	$275.6 \pm 19.1_{stat}$	31.6/16

Table 1: Fit values of the sidereal anisotropy. The first column is the corresponding figure. The values of the first harmonic fit amplitude and phase together with their statistical uncertainties are displayed in column two through three. The last column is the χ^2/ndf for the first harmonic fit to the one-dimensional projection.

Figure	A_{SOL} (10^{-4})	ϕ_{SOL} (hr)	χ^2/ndf
Fig.4.b	$6.7 \pm 2.0_{stat.}$	$6.0 \pm 1.1_{stat}$	23.6/16

Table 2: First harmonic fit values of the solar dipole anisotropy together with their statistical uncertainties

Figure	A_{ASID} (10^{-4})	ϕ_{ASID} (hr)	χ^2/ndf
Fig.4.d	$1.5 \pm 2.0_{stat.}$	$5.4 \pm 4.9_{stat}$	8.7/16

Table 3: First harmonic fit values of the anti-sidereal anisotropy together with their statistical uncertainties

6 Conclusion

In the contibution, we presented the results on the the large-scale sidereal anisotropy of the galactic cosmic ray intensity at 300 TeV, based on the large data sample (3.1×10^8 air shower events) obtained from long-time and high-stability observations (fifteen years) by the Tibet AS array. The most significant structure, an excess localized at (α = 271.0°, δ = 22.1°), with a significance of 7.3σ (pre-trial) or 5.4σ (post-trial) and an optimized smoothing of 29°. The maximum relative intensity region with an intensity of $\sim 2.0\times10^{-3}$ is around ($\alpha = 255.0°$, $\delta = -13.9°$), that is close to the highest excess region observed by IceCube at 400 TeV. The origin of this anisotropy is unknown.

Acknowledgment: The collaborative experiment of the Tibet Air Shower Arrays has been performed under the auspices of the Ministry of Science and Technology of China and the Ministry of Foreign Affairs of Japan. This work was supported in part by a Grant-in-Aid for Scientific Research on Priority Areas from the Ministry of Education, Culture, Sports, Science and Technology, by Grantsin- Aid for Science Research from the Japan Society for the Promotion of Science in Japan, and by the Grants from the National Natural Science Foundation of China (No.11135010).

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