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Search for the Large-Scale Cosmic-Ray Anisotropy at 10^{18} eV with the Telescope Array Surface Detector

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Abstract: We report on the search for the large-scale cosmic-ray anisotropy in the energy region between $10^{18.0}$ eV and $10^{18.4}$ eV in the northern sky, based on the dataset taken during the period between 2008 May and 2012 October with the surface detector of the Telescope Array experiment (TA SD). The number of analyzed air shower events is approximately 1.6 times larger than that of the AGASA observation which claimed the presence of the large-scale anisotropies before. The expected anisotropy map observed by the TA SD is demonstrated using the MC events including the artificial anisotropies assuming the AGASA results. This map shows detectable intensities with the TA SD around the positions of the AGASA anisotropies. We find, however, no such strong excesses or deficit in the actual TA SD data.

Keywords: Telescope Array, Cosmic rays, Ultra high energy, Ankle region, Anisotropy

1 Introduction

The energy region around 10^{18} eV (EeV) is thought to be a transition from cosmic rays of galactic origin to extra-galactic origin. Many cosmic-ray experiments have searched for the cosmic-ray anisotropy to identify its origin in this energy region. The AGASA and the Akeno-20 km^2 array (Hereafter, simply 'AGASA'), which had operated over 15 years, reported results that indicate the presence of the large-scale anisotropies in the energy region around $10^{18.0}$ eV [1, 2]. In this observation, the cosmic-ray excesses were found around the Galactic center (G.C.) and the Cygnus region with the statistical significance 4.5σ and 3.9σ, respectively, in the energy region between $10^{18.0}$ eV and $10^{18.4}$ eV. They also found a large-scale cosmic-ray deficit near the Anti-Galactic center (Anti-G.C.) with the statistical significance $\sim -4\sigma$ level. On the contrary, the Auger experiment rejected such a large enhancement near the Galactic center which was observed by the AGASA [3].

In this paper, we will report on the search for large-scale cosmic-ray anisotropy at 10^{18} eV energy region with the Telescope Array Surface Detector (TA SD) which has the largest effective area in the northern hemisphere.

2 Experiment

The TA SD is the largest cosmic-ray detector in the northern hemisphere, which consists of the surface detector (SD) array [4] and three fluorescence detector (FD) stations [5, 6]. The TA has been fully operating at Millard Country, Utah, USA (39.30°N, 112.91°W; approximately 1,400 m above sea level), since 2008. The TA SD consists of 507 plastic scintillation detectors of 3 m^2 placed at grid point 1.2 km apart, and its coverage area is approximately 700 km^2. For more details, see elsewhere [7]. In this analysis, we will use the data taken between 2008 May 11th and 2012 October 15th by the TA SD.

3 Air Shower Analysis

The air shower reconstruction and data selection are optimized for the low-energy air showers around 10^{18} eV based on the standard reconstruction code developed in the cosmic-ray anisotropy, energy spectrum and composition studies [8, 9]. The number of triggered events is 10^6 with the three-fold coincidence of adjacent SDs with greater than three single muons within 8 μs [7]. The number of remaining events after the standard cuts is relatively small ~18,000 events due to hard parameter cuts to mainly improve the energy resolution for the spectrum study. In order to search for the large-scale anisotropy, the air shower statistics is more important than the energy resolution if the anisotropy gradually changes with the energy. Since the scale of anisotropies observed by the AGASA may be more than 10°, the good angular resolution to search for is unnecessary. Therefore, we drastically loosen the event cuts in the air shower reconstruction to improve the air shower statistics. Table 1 shows the number of remaining events with only four criteria which are defined as the loose cuts. The number of air showers after the loose cuts is increased by ~10 times, which corresponds to 172,125 events, compared with that of the standard cuts.

Fig. 1 shows the energy distributions by the Monte Carlo (MC) simulation assuming protons. Closed circles and triangles show reconstructed energy spectra of the data after the loose and standard cuts, respectively. The solid and dashed histograms show the energy spectra by the MC simulations after the loose and standard cuts, respectively. In this figure, one can see that the reconstruction efficiency with the loose cuts around 1 EeV is increased by 10 times compared with that of the standard cuts. This is a remarkably advantage to search for the large-scale anisotropy at EeV energy region.

Cut parameters	# of events
# of triggered events	1,019,131
# of SDs ≥ 4	266,518
Pointing direction error $\leq 10^\circ$	261,481
Zenith angle $\theta \leq 60^\circ$	242,693
Reconstructed energy > 0.5 EeV	172,125

Table 1: Loose-cut parameters in this analysis and the number of remaining events.

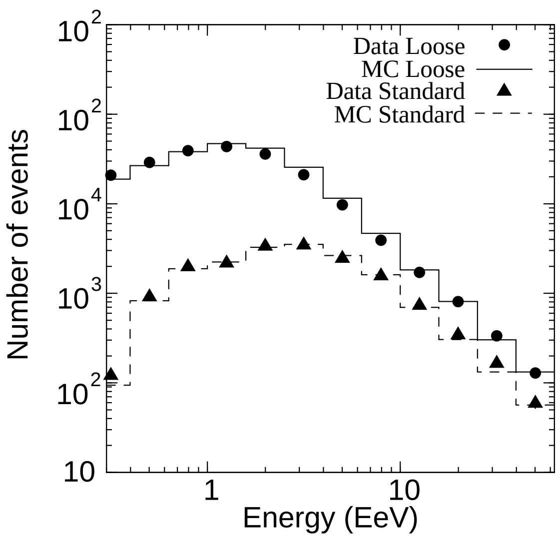

Fig. 1: Reconstructed energy spectra. Closed circles and triangles show energy spectra of the experimental data after the loose and standard cuts, respectively. Solid and dashed histograms show energy spectra by the MC simulation after the loose and standard cuts, respectively.

We also optimize the reconstruction method of arrival direction for the low-energy air showers based on the modified Linsley time-delay function [10] described as

$$T_{\mathrm{d}} = a\left(1+\frac{r}{30}\right)^{1.5}\rho^{0.5}, \tag{1}$$

where T_{d} is the time delay of air shower particles from the shower plane (ns), r is perpendicular distance from the shower axis (m), ρ is the pulse height per unit area (VEM/m^2), VEM means Vertical Equivalent Muon which is the average pulse height by vertical penetrating muons in the detector, "a" is the Linsley curvature parameter [11]. The "a" parameter in this analysis is optimized as $a(\theta) = 2.2\cos(1.1\,\theta)$ by the MC simulation depending on the zenith angle θ. This improves the angular resolution by 20% for air showers around 1 EeV, compared with the standard reconstruction method, although the angular resolution above 10 EeV worsens by 10%. The angular resolution with the loose-cut data is estimated to be overall 3.0° above 1 EeV, although it depends on the zenith angle of the air shower. This is good enough to search for the large-scale cosmic-ray anisotropy.

The energy is estimated from a lateral distribution fit with the same form used by the standard analysis [9, 12]. First, we calculate the $S(800)$, the density of air shower particles at lateral distance of 800 m from the core, by the lateral distribution fit. Then, the $S(800)$ is converted to the energy by a look-up table in $S(800)$ and zenith angle determined from the MC simulation using the loose-cut events. The energy resolution is estimated to be $^{+50}_{-35}$% around 1 EeV energy region.

With the loose-cut events, we also search for steady point-like sources of neutral particles around EeV energy in the northern sky. For detailed results, see elsewhere [13].

4 Background Estimation

The various background estimation methods have been developed to analyze the cosmic-ray anisotropy. As a simple method, the distribution of the air shower directions generated by the MC simulation is directly compared with the data. However, the MC simulation usually dose not reproduce the data perfectly due to the simulation model dependence and meteorological effects which are difficult to reflect in the MC simulation. As the other strategy, the background can be estimated by the data itself without the MC simulation. In order to estimate background of the large-scale anisotropy $\sim 10^\circ$ scale, we adopt the time-swapping method which is widely accepted method of background estimation [14, 15]. A direction of the air shower event is expressed by three parameters, the zenith angle θ, the azimuthal angle ϕ, and time t. With the time-swapping method, a time stamp of each event is randomly replaced to the time stamp of any other event. The time stamp never be used twice. Thus, all the air shower events are randomly swapped by replacing the time stamp. This swapped dataset still conserves θ and ϕ distributions, and daily/seasonal event rate variation due to the meteorological effects, while true signals distribute over other directions and smeared on the equatorial coordinates. Therefore, the swapped dataset can be used for the good background estimator. Finally, 20 such swapped datasets are generated by the different seeds of the random number, and an averaged background dataset is created from them to compare with the original event distribution.

5 Reconstruction of the AGASA Anisotropy

The AGASA has reported results that indicate the presence of three large-scale anisotropies between $10^{18.0}$ eV and $10^{18.4}$ eV [1, 2]. One is the 22% enhancement near the G.C. with the statistical significance $+4.5\sigma$. The other $+8\%$ enhancement is located around the Cygnus region with the statistical significance $+3.9\sigma$. A deficit is seen near the Anti-G.C. by approximately -8% with the statistical significance $\sim -4\sigma$. However, it is difficult to define intrinsic shape of anisotropy, because these anisotropies were averaged over large circles of 20° radius by the analysis procedure. Therefore, we define intrinsic shape of anisotropies assuming a few hypothesises. First, we simply assume the 2-Dimensional (2D) Gaussian shape. The assumed intensity of anisotropy $I(\alpha,\delta)$ on the equatorial coordinates with the right ascension (R.A. or α) and the declination (Dec. or δ) is expressed by

$$I(\alpha,\delta) = A\ \exp\left(-\left(\frac{(\alpha-\alpha_{\rm m})^2\cos^2\delta + (\delta-\delta_{\rm m})^2}{2\sigma_{\rm s}^2}\right)\right), \tag{2}$$

where A denotes the amplitude of anisotropy, $\alpha_{\rm m}$ (R.A.) and $\delta_{\rm m}$ (Dec.) denote the center coordinates of anisotropy, $\sigma_{\rm s}$ denotes the standard deviation of anisotropy. The A is normalized to the amplitude of the AGASA anisotropy averaged over a circle of the radius 20°. The $\sigma_{\rm s}$ of the 2D Gaussian is assumed to be 13° for the following reasons. When the anisotropy shape is assumed to be the 2D Gaussian, and the background events (noise) dominate over the anisotropy excess or deficit (signals), the optimal search window radius $R_{\rm sw}$ maximizing the S/N (Signal-to-Noise) ratio is calculated to be $1.58\sigma_{\rm s}$. Suppose the search window radius $R_{\rm sw} = 20°$ which was chosen in the analysis is optimized to the Gaussian shape, the $\sigma_{\rm s}$ should be $\sim R_{\rm sw}/1.58 \simeq 13°$. Fig. 2 shows the assumed AGASA anisotropies formed by the 2D Gaussian shapes with the $\sigma_{\rm s} = 13°$. The relative intensities in this map are averaged over 20° radius circle at each coordinate. In this figure, the open circles indicate the center position of the AGASA anisotropies near the G.C. ($\alpha_{\rm m} = 280°, \delta_{\rm m} = -17°$) and the Cygnus region ($\alpha_{\rm m} = 305°, \delta_{\rm m} = 45°$) respecviely. The peak of deficit is located near the Anti-G.C. ($\alpha_{\rm m} = 115°, \delta_{\rm m} = 30°$). These are overall reproduced the anisotropies observed by the AGASA. Using this relative intensity map, we generated MC sample events including the artificial anisotropies. Then, the expected map analyzed by the time-swapping method will be demonstrated, and it will compare with the actual TA SD results.

6 Results and Discussions

We analyze the air shower dataset collected by the TA SD from 2008 May 11th to 2012 October 15th. The number of analyzed air shower events is 79,396 events in the energy region between $10^{18.0}$ eV and $10^{18.4}$ eV. This corresponds to approximetaly 1.6 times larger statistics than that of the AGASA observation which claimed the presence of the large-scale anisotropies [1]. Fig. 3(a) shows the expected significance map with the TA SD by the time-swapping method, using the MC sample events assuming the AGASA anisotropies as shown in Fig.2. The number of analyzed MC sample events is the same statistics of the actual TA SD data. Fig. 3(b) shows the significance drawn by the time-swapping method using the actual dataset collected by the TA SD. The events in maps are summed over 20° radius circles centered at $1° \times 1°$ grids on the equatorial coordinate. In Fig. 3(a), detectable anisotropies are seen at the statistical significance approximetaly $\pm(5-6)\sigma$. On the contrary, in Fig. 3(b), there is no significant anisotropy. It means that the TA SD results do not support such large excess and deficit.

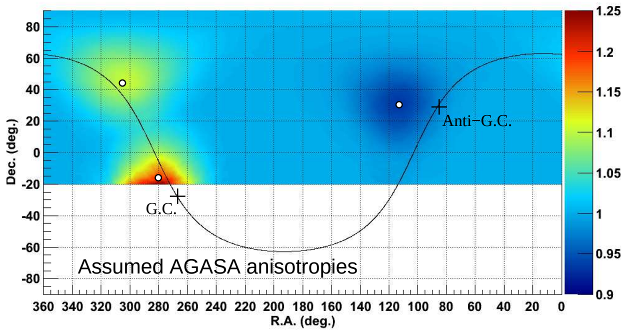

Fig. 2: Assumed AGASA anisotropy formed by the 2D Gaussian shape with the $\sigma_{\rm s} = 13°$. The color contour shows the relative intensities which are averaged over 20° radius circle at each coordinate. The open circes show the center positions of assumed the AGASA anisotropies [1]. The cross marks indicate the Galactic center (G.C.) and the Anti-Galactic center (Anti-G.C.), while the solid curve indicates the Galactic plane.

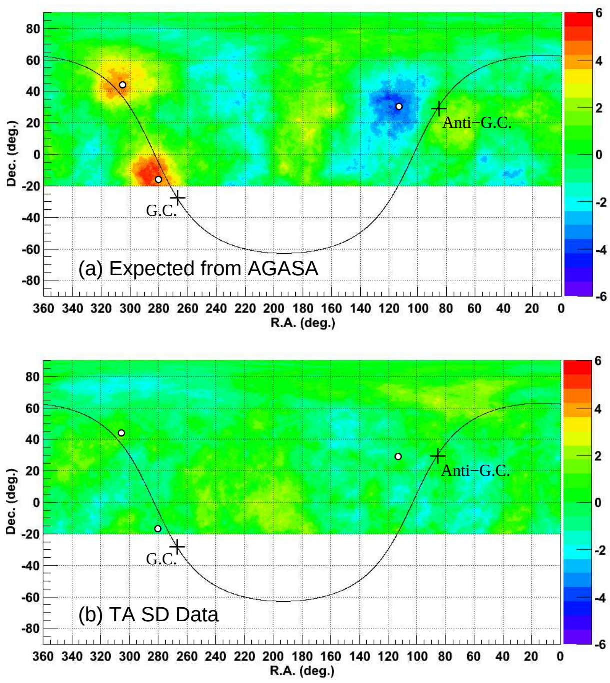

Fig. 3: (a): Expected significance map with the TA SD using the MC sample events assuming the AGASA anisotropies as shown in Fig.2. The number of analyzed events is the same statistics of the air shower events observed by the TA SD. (b): Actual significance map of the anisotoropy observed by the TA SD in the energy range between $10^{18.0}$ eV and $10^{18.4}$ eV. The events in maps are summed over 20° radius circles centered at $1° \times 1°$ grids on the equatorial coordinate. The open circles show the center positions of assumed anisotropies. The cross marks indicate the Galactic center (G.C.) and the Anti-Galactic center (Anti-G.C.), while the solid curve indicates the Galactic plane.

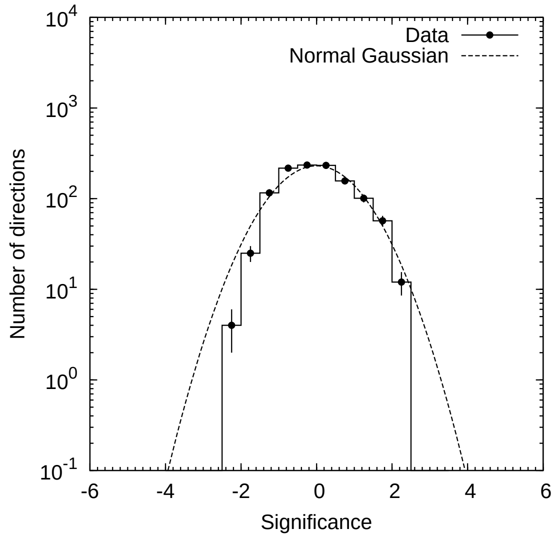

Fig. 4: Histogram shows significance distribution of samples on the grid 3° spacing in the map as shown in Fig. 3(b). The dashed curve is the expected normal Gaussian distributions.

Fig. 4 shows the significance distribution of samples on the grid 3° spacing in the actual TA SD map as shown in Fig. 3(b). The normal Gaussian as shown by the dashed curve is consistent with the data. It means there is no significant excess or deficit beyond statistical fluctuation.

Note that the possible energy scale difference between the TA and the AGASA is estimated to be $\sim$28%. Therefore, we also search for the large-scale anisotropy in the tuned TA energy range to the AGASA energy scale which corresponds to the energy bewteen $10^{17.88}$ eV and $10^{18.28}$ eV. As a result, there is no significant anisotropy in this energy range, although the number of analyzed air shower events is increased by $\sim$5%.

7 Summary

We search for the cosmic-ray large-scale anisotropy at the energy range between $10^{18.0}$ eV and $10^{18.4}$ eV in the northern sky. The air shower reconstruction and data selection are optimized for the EeV air showers. The number of air showers above 0.5 EeV is increased by $\sim$10 times after the optimization, compared with the standard analysis method. In order to search for the large-scale anisotropy, the time-swapping method is adopted to these cosmic-ray air showers taken by the TA SD during the period between 2008 May and 2011 October. The number of analyzed air shower events is approximetaly 1.6 times larger than that of the AGASA observation which claimed the presence of the large-scale anisotropies in the energy region between $10^{18.0}$ eV and $10^{18.4}$ eV. The expected anisotropies assuming the AGASA results show detectable intensity with the TA SD. We find, however, no such significant excess or deficit, in this period and energy range. We also search for the large-scale anisotropy in the tuned TA energy range to the AGASA energy scale which corresponds to the energy bewteen $10^{17.85}$ eV and $10^{18.25}$ eV. As a result, there is also no significant anisotropy.

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