Search for Anisotropy in the Ultra High Energy Cosmic Ray Spectrum using the Telescope Array Surface Detector

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Abstract

The Telescope Array (TA) experiment is located in the western desert of Utah, USA, and observes ultra high energy cosmic rays (UHECRs) in the Northern hemisphere. At the highest energies, $E > 10$ EeV, the shape of cosmic ray energy spectrum may carry an imprint of the source density distribution along the line of sight different in different directions of the sky. In this study, we search for such directional variations in the shape of the energy spectrum using events observed with the Telescope Array's surface detector. We divide the TA field of view into two nearly equal-exposure regions: the "on-source" region which we define as $\pm 30°$ of the supergalactic plane containing mostly nearby structures, and the complementary "off-source" region where the sources are further away on average. We compare the UHECR spectra in these regions by fitting them to the broken power law and comparing the resulting parameters. We find that the off-source spectrum has an earlier break at highest energies. The chance probability to obtain such or larger difference in statistically equivalent distributions is estimated as $6.2 \pm 1.1 \times 10^{-4}$ (3.2σ) by a Monte-Carlo simulation. The observed difference in spectra is in a reasonable quantitative agreement with a simplified model that assumes that the UHECR sources trace the galaxy distribution from the 2MRS catalogue, primary particles are protons and the magnetic deflections can be neglected.

Keywords: Ultra High Energy Cosmic Ray, Large Scale Structure, Anisotropy, Spectrum, Composition

INTRODUCTION

Ultra high energy cosmic ray (UHECR) primaries lose a notable fraction of energy in interactions with photons of cosmic microwave background radiation (CMBR) while propagating over distances comparable to the size of local cosmological structures such as voids and clusters of galaxies. The attenuation length depends on the particle type and energy. Protons which have energy $> 10^{19.7}$ eV lose the major part of their energy in pion photoproduction. Consequently, the spectrum of protons is expected to show the suppression of flux at these energies, which is known as the GZK cut off [1, 2]. Another relevant process for protons propagating in the CMBR is e^+e^- pair creation. This reaction is important for protons with $E \simeq 10^{18.6}$ eV. Heavier nuclei also loose energy in interactions with photon background fields through the photo-disintegration processes [3] that typically lead to splitting off of individual nucleons. The mean free path of this process also becomes smaller at higher energy.

The losses alter the UHECR energy spectrum in a way that depends on the distance to the source. As a result, UHECR energy spectra may be different in different areas on the celestial sphere: harder in the direction of nearby structures and softer where the large-scale concentrations of matter are further away. In this work, we confront this expectation with the TA data by comparing energy spectra of UHECR in regions which contain large number of nearby objects with those corresponding to local voids. This approach is complementary to the anisotropy studies focused on the distribution of arrival directions only.

EXPERIMENT AND DATASET

Telescope Array (TA) experiment [4] employs a hybrid approach to the detection of UHECR with energies E $> 10^{18}$ eV. Cosmic rays are observed using both fluorescence telescopes and a surface detector array. The surface detector of TA consists of 507 scintillation counters deployed on a square grid with 1.2 km spacing, covering an area about 670 km^2 [5]. The operation of the surface detector started in 2008. Its duty cycle is 95% on average. TA has accumulated the largest exposure in the Northern hemisphere. The fluorescence telescopes have a much smaller duty cycle of $\sim$ 9% [6]. In this analysis, cosmic-ray events with energies, $E > 10^{19}$ eV observed by the surface detector of TA in the period from May
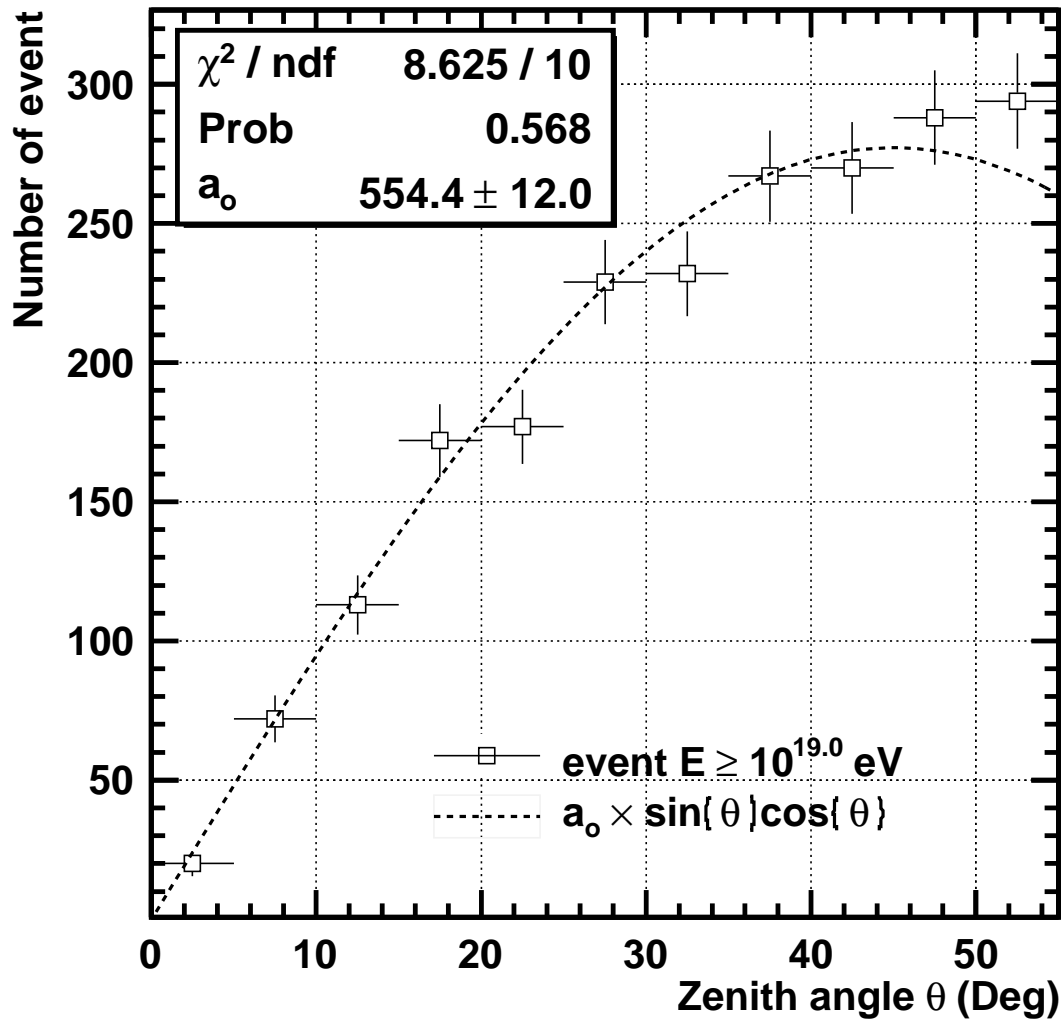
FIG. 1. The zenith angle distribution of observed shower events with energy $E \geq 10$ EeV.

2008 to May 2013 are used.

From Monte Carlo simulations, the trigger efficiency of cosmic-ray showers at zenith angles of less than $55°$ reaches 100% in the energy range greater than 10^{19} eV. Corresponding estimated energy resolution is about 20%, while the angular resolution is better than $2°$[4, 7]. The distribution of the zenith angles of the observed events is shown in Figure. 1. It agrees well with the geometrical exposure which is also shown on the plot for comparison.

ANALYSIS FOR SUPER GALACTIC PLANE (SGP)

In this analysis, we divide the sky into two parts: the one containing a larger number of nearby objects and another one with a lesser number of nearby objects. These parts will be referred to as the "**on-source**" and "**off-source**" areas, respectively. We then compare the energy spectra in the on-source and off-source sky regions. As the division criterion we use the positions of sources with respect to the Super Galactic Plane (SGP). The SGP is a major structure in the nearby Universe containing a number of massive galaxy clusters at distances of a few tens of Mpc [8]. For the analysis, we choose the on-source region as the region of the sky containing the SGP. The exposure of the TA experiment is almost equally divided when we define a sky within ±30° of the SGP as the on-source area and the rest as the off-source area. The fractions of the total exposure corresponding to the on- and off-source areas are 52% and 48%, respectively. Another — technical — advantage of this choice is that the zenith angle distributions in the two regions are practically identical. (Detailed discussion of systematic effects is given in the next section.) In principle, one may base the choice of the on- and off-source regions directly on the matter distribution in the nearby Universe. However, to use matter distribution directly in the simple approach adopted here, all the details about the UHECR propagation, composition at high energies, etc, are needed. Given the existing uncertainties and limited statistics, we find the more simple approach adopted here to be more than adequate at the present stage.

Once the on- and off-source regions are fixed, we first compare the energy distributions of the observed events coming from these regions. Figure. 2 shows the energy distribution of all the observed showers obtained for the entire exposure (thin histogram), and separately for the On-source and Off-source areas (filled and empty squares, respectively). The lines show the fits to these distributions by a broken power law, with the fitting function defined as follows:

$$\frac{\Delta N(E)}{\Delta \log_{10}\left(\frac{E}{E_0}\right)} = C_0 \left(\theta(E_b - E) \left(\frac{E}{E_0}\right)^{-\alpha_1} + \theta(E - E_b) \left(\frac{E_b}{E_0}\right)^{-\alpha_1 + \alpha_2} \left(\frac{E}{E_0}\right)^{-\alpha_2} \right) \quad (1)$$

Here, $E_0 = 1$ EeV, C_0 is a normalization constant proportional to the total number of events, while $\alpha_{1,2}$ are spectral indexes below and above the break, respectively. The best fit
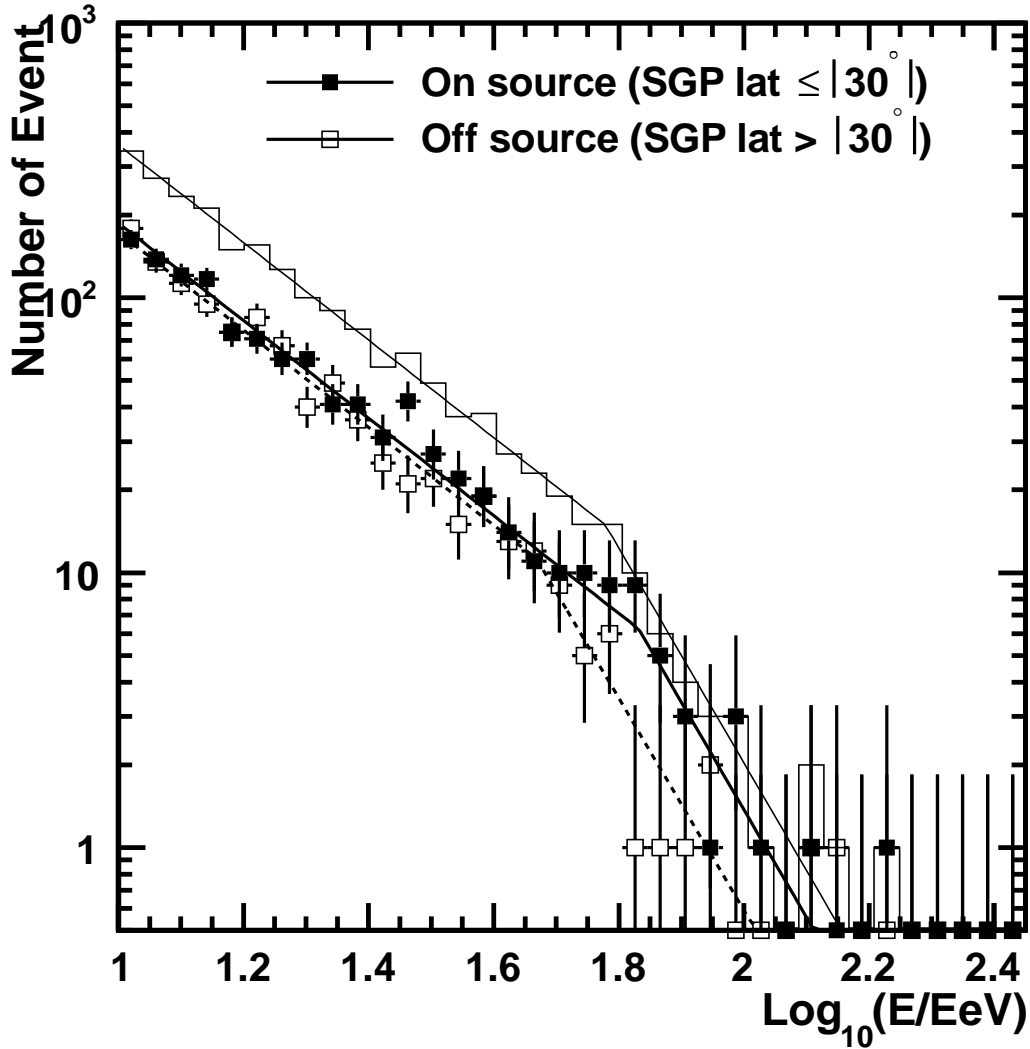
FIG. 2. The energy distributions of observed shower events for the on- and off-source areas. The black histogram shows distribution of all events. Closed and open symbols show energy distributions observed in On-source and Off-source regions respectively.

parameters for the energy distribution obtained for the entire exposure are

$$C_0 = 2.14^{+0.34}_{-0.30} \times 10^4 \qquad \alpha_1 = -1.775^{+0.053}_{-0.053}$$
$$\log_{10}(E_b/\text{EeV}) = 1.778^{+0.040}_{-0.068} \qquad \alpha_2 = -3.91^{+0.64}_{-0.66} \tag{2}$$

This fit is shown by the thin solid line on Figure. 2. When fitting the energy distributions in the on- and off-source regions, the slope before the break, α_1, is set to the value obtained

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Region	C_o	α_1	$\log_{10}(E_b/EeV)$	α_2
All	$2.14^{+0.34}_{-0.30} \times 10^{+4}$	$-1.775^{+0.053}_{-0.053}$	$1.778^{+0.040}_{-0.068}$	$-3.91^{+0.64}_{-0.66}$
On source	$(1.1128 \times 10^{+4})$	(-1.775)	$1.832^{+0.069}_{-0.041}$	$-3.91^{+0.70}_{-1.30}$
Off source	$(1.0286 \times 10^{+4})$	(-1.775)	$1.668^{+0.052}_{-0.053}$	$-3.86^{+0.58}_{-0.82}$

TABLE I. Parameters of the best fit broken power law in the SGP case.

from the fit to the distribution for the entire exposure, equation. (2). At higher energy in this energy range, mean free path of cosmic ray become shorter. It is expected that the differences at high energies due to different attenuation of flux for close and far sources, while negligible differences at low energies are expected. There is additionally the effect of increased isotropization in a coherent magnetic field at the lowest energy bins especially in case of nuclei other than proton. However, non-zero difference in spectrum slope would be exist. The small difference at lower energy side will be reflected to a change of α_2 and E_b those are free parameter in the fitting. The normalization, C_0, is scaled to the corresponding fraction of the exposure in each region, while $\log_{10}(E_b/E_0)$ and α_2 are set free and obtained from the fitting in corresponding areas. There are bins with zero count at highest energy bins. Those bins are also included in the likelihood calculation. The resulting broken power law functions are plotted in Figure. 2 as solid and dashed lines. The results of the fit are summarized in Table. I. Figure. 3 shows the best-fit values of parameters together with the confidence contours in the $\log_{10}(E_b/E_0) - \alpha_2$ plane. As one can see, there is a difference in break energy between the on-source and off-source areas, $\Delta \log_{10}(E_b/E_0) = 0.16$. Off-source, the break occurs at lower energies, in agreement with expected larger attenuation for larger source distances. The fraction of events above the break in the off-source region, $N_{off}(E > E_b)/N_{all}(E > E_b)$, is 0.337 ± 0.050 instead of 0.48 as expected from the exposure ratio.

To estimate the chance probability that the observed difference in the energy distribution occurred as a result of a fluctuation, we performed the following simulation. In each energy bin the events have been randomly re-labeled as the on- and off-source events following the binomial distribution with the parameters that correspond to the ratio of the corresponding exposures, that is the on-source probability 0.52 and the off-source probability 0.48. After this re-shuffling, the new On-source and Off-source energy distributions have been
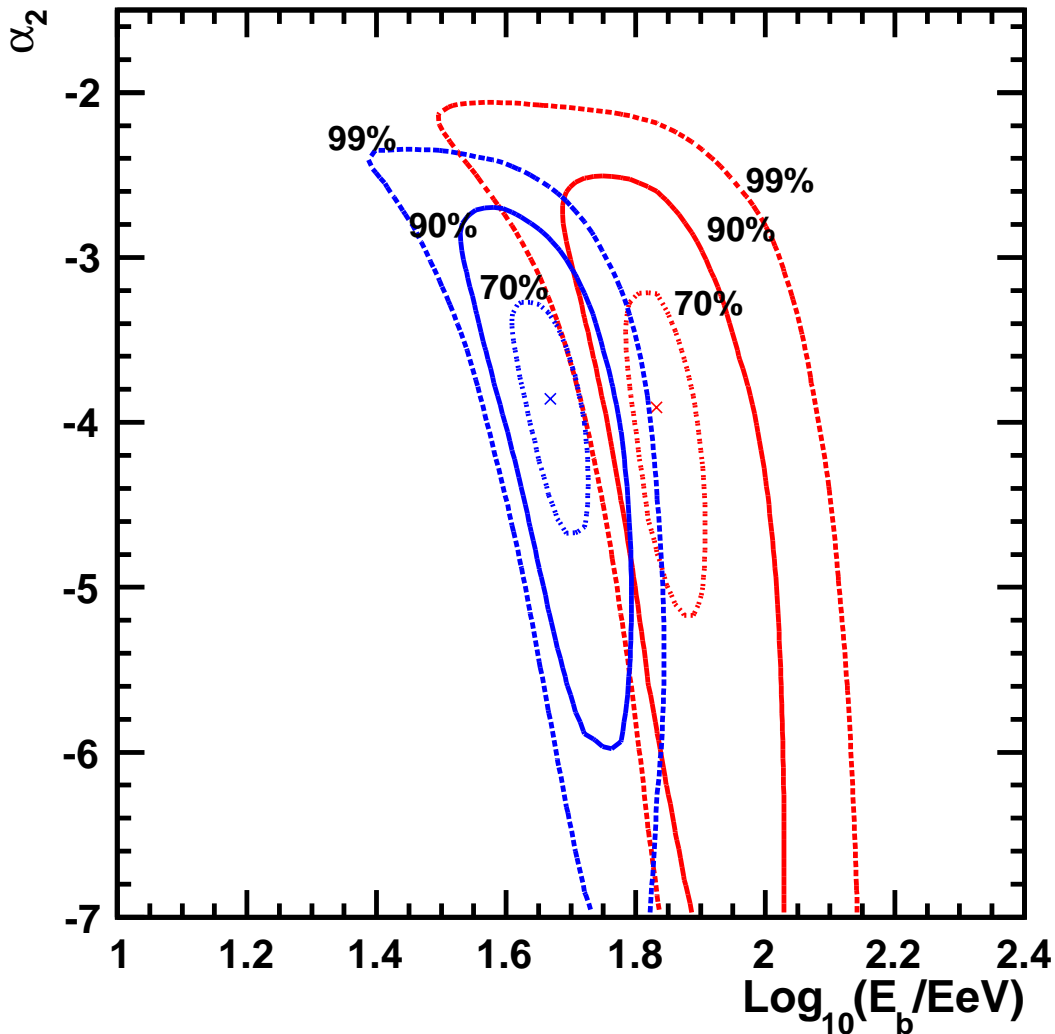
FIG. 3. Contours of $\delta \log L$ in the plane of E_b and α_2 in the SGP case. Blue and red colors denote 70%, 90% and 99% confidence levels for the off- and on-source regions, respectively.

constructed and fitted by the broken power laws in exactly the same way as the original data, giving the new values of the break energies and the numbers of events after the break. This procedure then has been repeated 5×10^4 times. Figure. 4 shows the distribution of occurrences of parameters that characterize the off-source energy distribution shape — the break energy E_b and the fraction of events above the break $N_{off}(E > E_b)/N_{all}(E > E_b)$. The horizontal axis corresponds to the off-source break energy and vertical axis to the event frac-
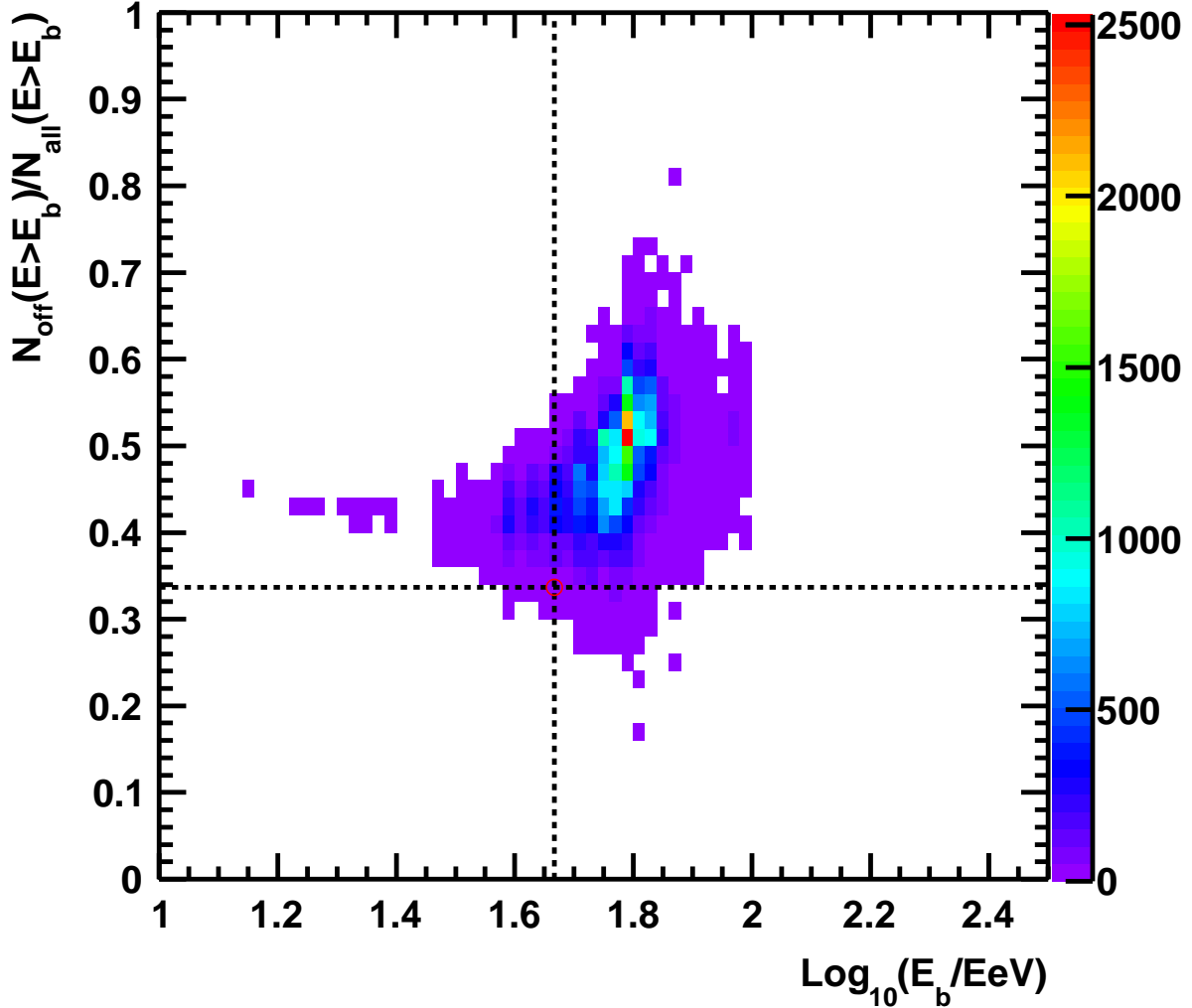
FIG. 4. Event fraction in the off-source region above the break energy versus $\log_{10}(E_b/EeV)$ obtained in Monte Carlo simulations. Red point and dashed line represents observed value in real data.

tion above the break energy. The values observed for the data are marked by the horizontal and vertical dashed lines which divide the parameter space into four regions.

The number of occurrences of parameters in the resulting four regions of the parameter space is summarized in Table II.

Following the predictions of the UHECR propagation models that suggest that the spectrum in the off-source region should have a lower break energy and a smaller number of

Condition	case	Fraction
$E_b > 10^{1.668} EeV$, $\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.337$	45031	$0.9008(\pm 0.0013)$
$E_b < 10^{1.668} EeV$, $\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.337$	4606	$0.0921(\pm 0.0013)$
$E_b < 10^{1.668} EeV$, $\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.337$	31	$0.00062(\pm 0.00011)$
$E_b > 10^{1.668} EeV$, $\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.337$	352	$0.00704(\pm 0.00037)$

TABLE II. The number of occurrences N with given break energy and number of events above the break, and the corresponding fractions.

events above the break, we consider a trial successful if it has both of these parameters smaller than in the data. The fraction of successful trials (third line in Table II) in our MC simulation is 31, which gives the p-value $p = 6.2 \times 10^{-4}$ (3.2σ).

SYSTEMATIC ERRORS

As the spectrum of UHECR is potentially sensitive to reconstruction biases, an important question is whether the on- and off-source regions correspond to the same observational conditions, notably the same zenith angle distribution of the events. For the adopted on- and off-source regions, the distributions of zenith angles of exposure are plotted in Figure. 5. The relative deviations of these distributions from the total (geometrical) exposure are shown on the bottom panel; one can see that they do not exceed several percent. The difference between the two regions in observing condition is thus negligible considering our statistics.

The time variation of the energy scale due to change in atmospheric conditions can be another source of a systematic error. To check its influence, the event rate with energies greater than $10^{19.0}$ eV was studied in anti-sidereal time [9]. The amplitude of fluctuations of the event rate in the anti-sidereal time was found to be at most 5% $\pm 3\%$. Given the observed spectral index around $10^{19.0}$ eV, this corresponds to the energy shift by $\sim 2.5\%$. One may estimate the effect of this possible energy shift by re-doing the calculation of the p-value with the event energies shifted by 2.5% upwards. The resulting p-value is 6.9×10^{-4} $(3.2\ \sigma)$, i.e., the effect of this uncertainty is negligible.
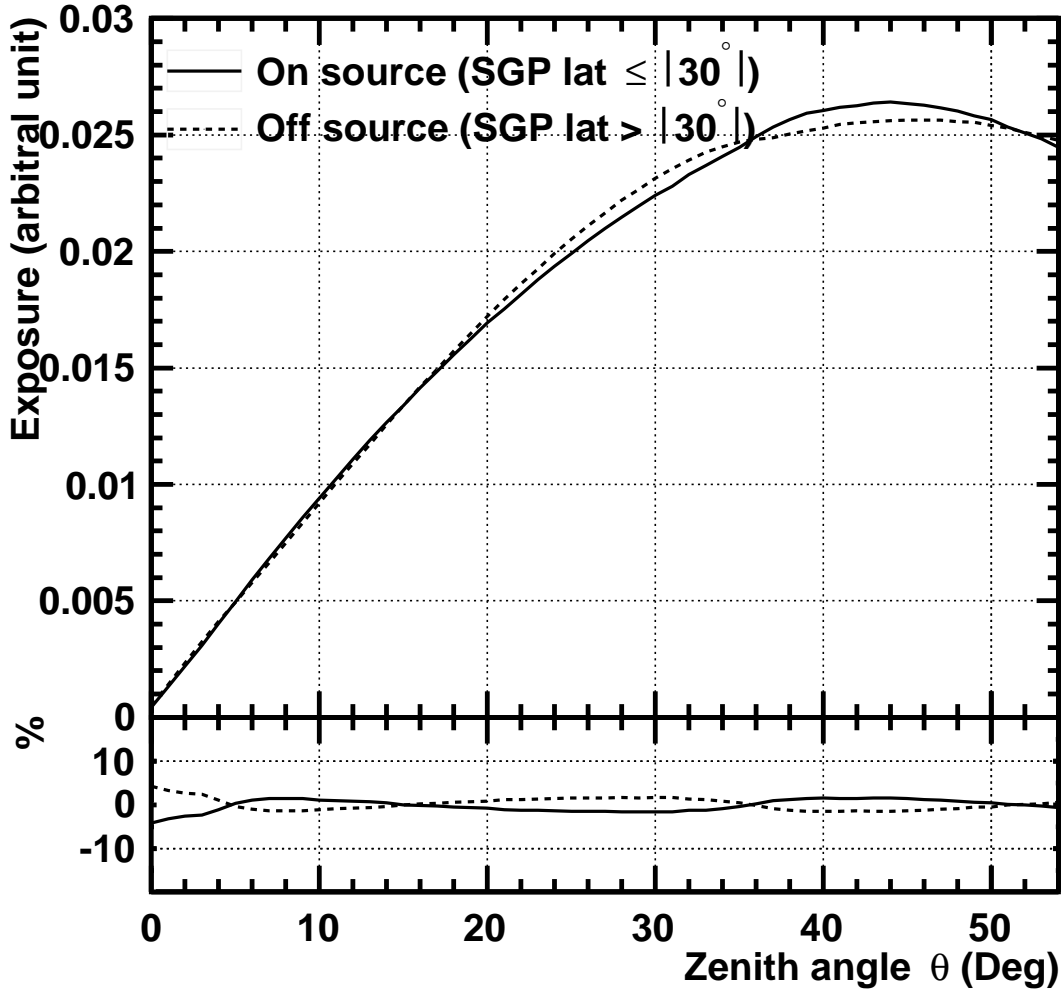
FIG. 5. The zenith angle distributions in On and Off source areas. The relative deviations of these distributions from the total (geometrical) exposure are shown on the bottom panel.

DISCUSSION

To see if the observed differences in energy distributions are compatible with model predictions, we performed a simplified numerical simulation using a propagation code CRPropa 2.2.0.4 [10] and the source distribution from the 2MRS catalogue [11] using the density profile calculation described in [12]. In a simplified expectation, when the composition at origin consists of nuclei, the expected difference of spectrum between on and off-source region start
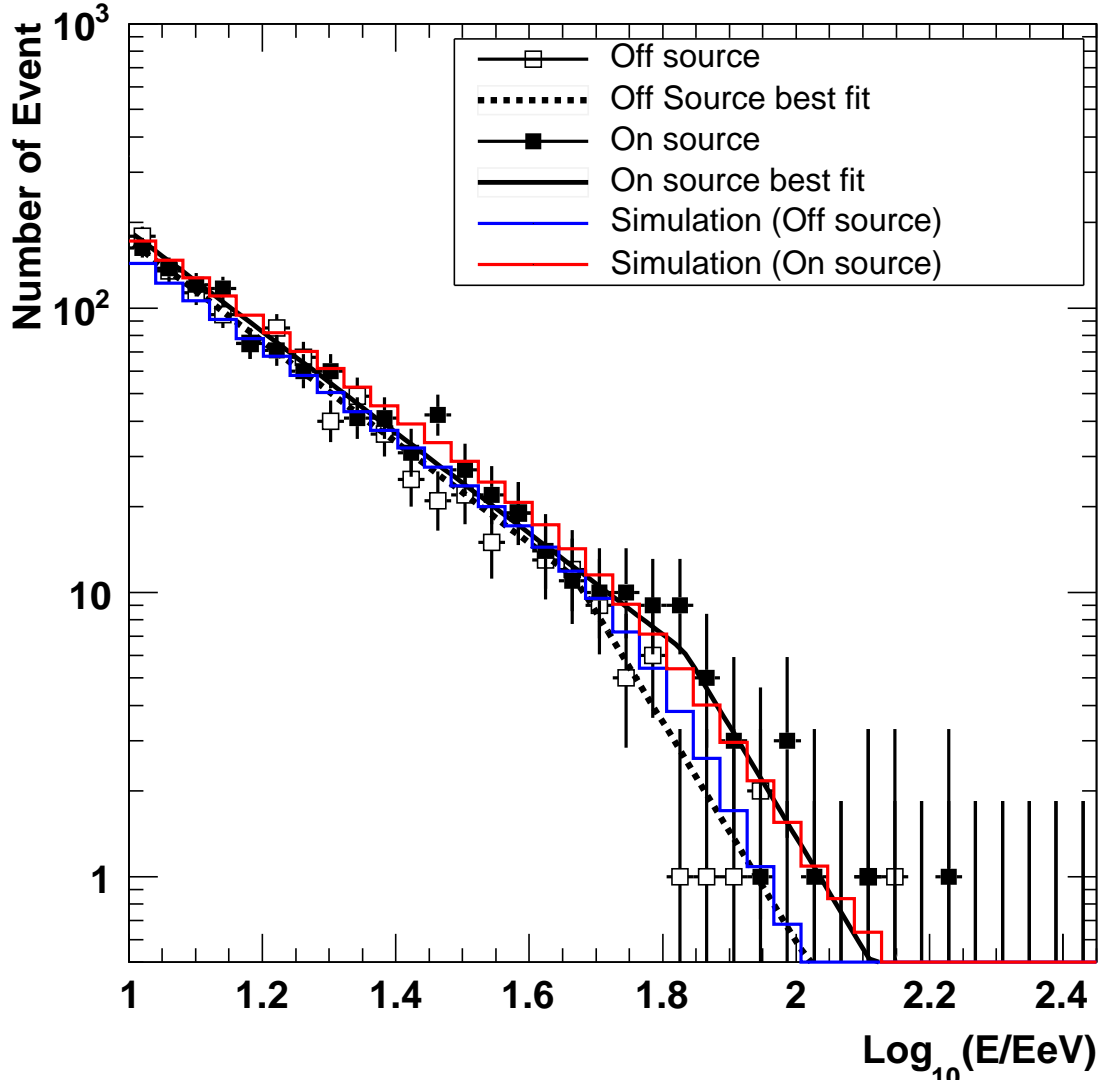
FIG. 6. Comparison of energy distributions expected for protons simulated with CRPropa 2.2.0.4 arriving from the sources with injection index of -2.2, evolution parameter of 7 and 2MRS density profile.

develop from lower energy and show gradual development as compared to the case of proton. That is because nuclei have photo-disintegration as a dominant energy loss process while proton have pion production with energy threshold. Figure. 6 displays the results. Here protons were assumed as primary particles. The injection index and evolution parameter were set to -2.2 and 7, respectively, as to reproduce the observed TA energy spectrum [13]. Simulations are done in one dimension assuming 0.1 nG random magnetic field. The

difference of the observed energy distributions in the on-source and off-source regions were, qualitatively, well reproduced by this simulation, given the simplifications made when modelling the propagation. A quantitative comparison with the theoretical predictions would require a more accurate modeling of the propagation, as well as a better understanding of the UHECR composition not available at present TA statistics.

SUMMARY

Using data obtained by the TA surface detector in first 5 years, a new approach to search for the anisotropy of UHECR is developed. It employs the modulation of the energy spectrum due to energy losses in the interactions with the CMBR during propagation of primaries. Such modulations occur in a different way for sources at different distances; as a result, the UHECR spectra may differ in region of the sky that contain nearby matter concentrations (sources are closer on average) and regions that do not contain such structures (sources are further on average). The TA field of view was divided into two almost equal-exposure parts: the on-source region within $\pm 30°$ from the SGP, and the complementary off-source region. The energy distributions of the observed TA events in these regions were fitted by a broken power law. The results of the fit are summarized in Table. I. The parameters that characterize the energy spectra in the two regions differ: in the off-source region the flux has earlier suppression as compared to the on-source region, in qualitative agreement with expectation from the propagation models. The chance probability that this difference arises as a result of a fluctuation in two statistically equivalent distributions was estimated to be $\sim 6.2 \times 10^{-4}$ (3.2σ). We conclude that there is a $\sim 3\sigma$ indication of the spectrum differences of UHECR in different regions of the sky in the Northern hemisphere. In on-source region, it is known there is a direction with excess of number of event which is found in a paper [14]. The excess is evaluated using events with energy above 57 EeV and by integrating number of events with area of 20°. The nature of this excess is not known yet. In this paper, the approach applied does not use specific threshold in energy and angular size. We believe that the approach proposed here can be developed further, and may help to reveal the sources of cosmic rays and their chemical composition.

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