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# Anisotropy search in the Ultra High Energy Cosmic Ray Spectrum in the Northern Hemisphere using latest data obtained with Telescope Array surface detector

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The Telescope Array (TA) experiment is located in the western desert of Utah, USA and observes ultra-high energy cosmic rays in the northern hemisphere. At the energies, the shape of the cosmic ray energy spectrum carries information of the source distribution. We present the search for differences in spectrum shape in different parts of the sky using latest data of TA surface detector (SD) data. From this study, we observe an apparent enhancement in the region of the northern sky that contain nearby objects, such as the super-galactic plane. Details of this analysis will be presented.

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## 1. Introduction

The expected acceleration site of UHECR are extra galacic object which have large volume or very strong magnetic fileld is in it's environment. In the ultra high energy rgime, cosmic ray nuclei lose energy during propagation over a few Mpc to 100 Mpc in distance. Since the attenuation length differs for each particle type, the observed spectrum shape encodes information of the distance distribution of acceleration sites and of energy deposition that depend on chemical composition. Proton of energy in excess of $10^{19.72}$ eV will interact with cosmic microwave background (CMB) and generate pion resulting in loss of energy. Thus the spectrum of proton cosmic rays is expected to show flux suppression known as GZK cut off [5, 8]. Another process is $e^{+} + e^{-}$ creation with infra-red background photon which have higher energy than CMB photon. Pair production is the dominant energy-loss proton around energies of about $10^{18.6}$ eV. These spectrum modulation of UHECR are described in [3, 7] . In any case, these effects signal a situation in which the spectra of celestial regions that do not contain the source are more attenuated from lower energies than those of celestial regions that do contain the source. This is shown in the figure. An example of a region with nearby matter is that around the super-galactic plane. In this contribution, we search for a change in the shape of the spectrum in this region.

## 2. Experiment and analysis

The Telescope Array(TA) experiment [2] is a hybrid detector which observe cosmic rays have energy E > $10^{18}$ eV using fluorescence telescopes and surface detector. The surface detector of TA consists of 507 scintillation counters deployed in 1.2km covering about 700 km$^2$. [1]. The energies of observed cosmic ray are calibrated against fluorescence detectors viewing the sky above the surface detector array. The TA surface detector started observation in 2008. Observation efficiency exceeded 95% for every every year of operation since the start. Now the accumulated exposure for UHECR is the largest in the northern hemisphere In this analysis, cosmic ray events with energies E> $10^{19.0}$ eV observed in the period May 2008 to May 2020 are included in a search for anisotropy in cosmic ray energy spectrum. For this analysis, the reconstruction resolution is about 20% for energy and about 2° for arrival direction [2, 6]. From Monte Carlo simulation, we find the detection efficiency to reach 100% for events above E > $10^{19}$ eV for the shower zenith angle < 55°. The zenith angle distribution of observed shower at zenith angle < 55° is plotted in Fig 1. In this analysis , we divide the sky covered by our exposure into just 2 parts. One is the area which contain nearby objects. Another is the area which does not contain close objects. In this paper, we note the former area as "**On source**" sky. another area as "**Off source**" sky. We performed analysis defining On and Off source area as follow. First the Super Galactic Plane (SGP) is a plane contains nearby galaxies of our Local Group [4]. Here we divide the TA exposure equally between the "on source" band with in ±30° about and "Off source" area outside that region. The fraction of TA exposure for each area is 52% and 48%. The zenith angle distribution for observing the On source and Off source area are plotted together in Fig.2. These distributions show no significant difference and indicate that that the two sets of events cover similar local angles on the ground.

In Fig.3 and Fig.4 compare the energy distributions of observed air shower events from these On and Off source areas. The shape of distributions are evaluated by a likelihood fit to piece-wise

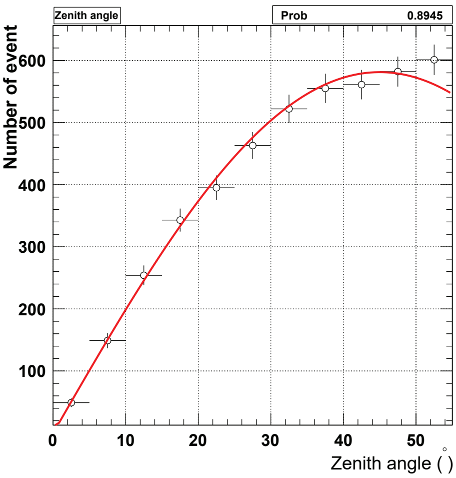


**Figure 1:** Zenith angle distribution of observed shower event with energy E ≥ 10 EeV.

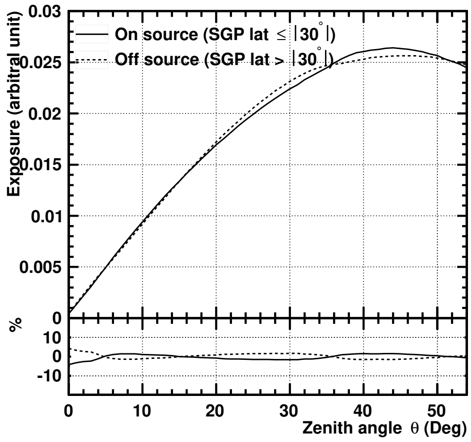


**Figure 2:** The zenith angle distribution while observing On source area and off source area is plotted

the power laws as shown in equation 1. The black line in Fig.3 shows best fit piece-wise power law fit expressed in equation 1 Here $E_o$ is 1EeV. $C_0$ represents normalization constant proportional to total number of events. $\alpha_{1,2}$ represents spectrum index for lower energies and higher energies than $E_b$ respectively.

$$\frac{\Delta N(E)}{\Delta \log_{10}\left(\frac{E}{E_o}\right)} = C_0 \left( \varepsilon\left(E, E_b\right) \left(\frac{E}{E_o}\right)^{-\alpha_1} + \left(1 - \varepsilon\left(E, E_b\right)\right) \left(\frac{E}{E_o}\right)^{-\alpha_2} \right) \tag{1}$$

$$\varepsilon(E, E_b) = \left\{ 1 : (E < E_b)\,, 0 : (E > E_b) \right.$$

With 5 year observation, best fit parameters for energy distribution obtained from entire exposure were $C_o = 2.14^{+0.34}_{-0.30} \times 10^{+4}$, $\alpha_1 = -1.775^{+0.053}_{-0.053}$, $\log_{10}(E_b/EeV) = 1.778^{+0.040}_{-0.068}$ and $\alpha_2 = -3.91^{+0.64}_{-0.66}$. In comparing the spectrum shapes between the On and Off source regions, what is of particular importance is the power index and normalization of events above the break at $E_b$. So in making the piece-wise power low fit for the two regions, we fixed $\alpha_1$ to the value obtained from the full data set and $C_0$ to the full data set value multiplied by the exposure fraction for that region. The break energy, represented by the ratio. $\log_{10}(E_b/Eo)$ and the power index $\alpha_2$ above the break are the free fit-parameters for the On and Off source regions. The results of the fit are shown by the solid and dashed lines for the On and Off source regions, respectively in Fig.3 and Fig.4. Fig.3 shows the result for the five year data. and Fig.4 is for the 12 year data.

Table.1 and 2 summarize the best fit parameters and errors. The likelihood function contour for $\alpha_2$ vs. $log_{10}(E_b/E_o)$ are plotted in Fig5 (5 years)and Fig6 (12 years).

We note that the break log energy, $log_{10}E_b$ is higher for the On source than the Off by 0.16 for both the five and 12 year data. For the five year data, the fraction of events above $E_b$ in the Off source region (over that for the full data set) $(N_{off}(E > E_b)/N_{all}(E > E_b))$ is $0.337 \pm 0.05$ instead of 0.48 the latter expected from exposure ratio. The same ratio for 12 year data was

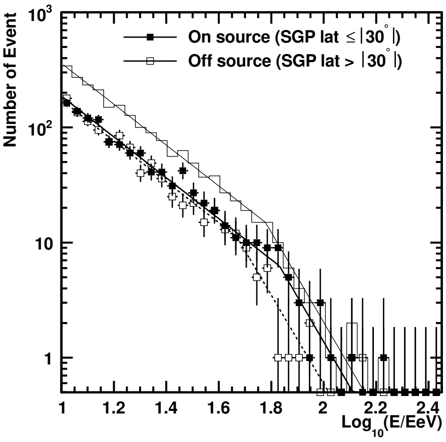


**Figure 3:** Energy distribution of observed shower event in 5 year. Black histogram shows entire events. Red and Blue histogram show energy distribution observed from On source area and Off source area respectively.

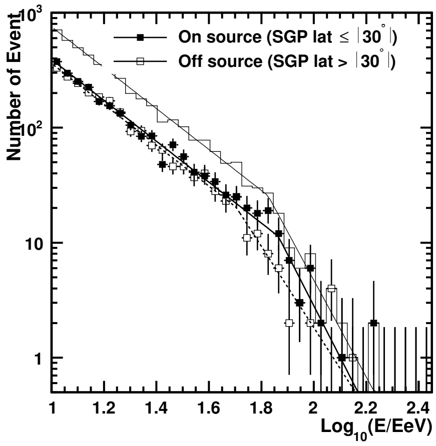


**Figure 4:** Energy distribution of observed shower event in 12 year. The lines are the same with Fig.3.

**Table 1:** Best fit Broke Power Law parameter for observed energy distribution (5year)

| Area | $C_o$ | $\alpha_1$ | $\log_{10}(E_b/EeV)$ | $\alpha_2$ |
|---|---|---|---|---|
| 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 | $(1.1128 \times 10^{+4})$ | $(-1.775)$ | $1.832^{+0.069}_{-0.041}$ | $-3.91^{+0.70}_{-1.26}$ |
| Off source | $(1.0286 \times 10^{+4})$ | $(-1.775)$ | $1.668^{+0.052}_{-0.053}$ | $-3.86^{+0.58}_{-0.82}$ |

**Table 2:** Best fit Broke Power Law parameter for observed energy distribution(12 year)

| Area | $C_o$ | $\alpha_1$ | $\log_{10}(E_b/EeV)$ | $\alpha_2$ |
|---|---|---|---|---|
| All | $4.519^{+0.458}_{-0.433} \times 10^{+4}$ | $-1.778^{+0.036}_{-0.034}$ | $1.825^{+0.026}_{-0.033}$ | $-4.20^{+0.49}_{-0.52}$ |
| On source | $(2.349 \times 10^{+4})$ | $(-1.778)$ | $1.865^{+0.036}_{-0.042}$ | $-4.46^{+0.77}_{-0.90}$ |
| Off source | $(2.169 \times 10^{+4})$ | $(-1.778)$ | $1.705^{+0.054}_{-0.028}$ | $-3.54^{+0.34}_{-0.42}$ |

$(N_{off}(E > E_b)/N_{all}(E > E_b))$ is $0.39 \pm 0.04$. This is within statistical uncertainty of the value from the five year data.

The chance probability of the different spectral shapes from statistical fluctuation is estimated by a simulation assuming both distribution are coming from population which is same as that for the full exposure. Specifically, in each iteration, we re-sampled the full set of events in each energy bin randomly to On and Off source according to binomial probability with the Off source exposure fraction as the p value.

Fig. 7 shows frequency distribution of $N_{off}(E > E_b)/N_{all}(E > E_b)$ vs $log_{10}(E_b/E_0)$ obtained from the five year data and simulation. Table. 3 lists chance probability obtained for each case. The observed value correspond to a probability $\sim 0.62 \times 10^{-4}$. The same distribution for

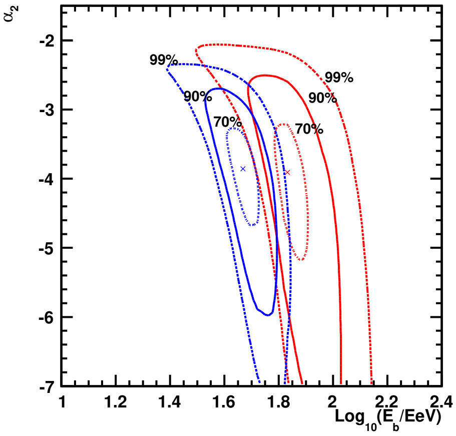


**Figure 5:** Contour of $\delta \log L$ and best fit parameter pair. Contour levels are drawn at 65%,90% and 95% level. For 'Off' and 'On' regions Blue and Red colours are used respectively.

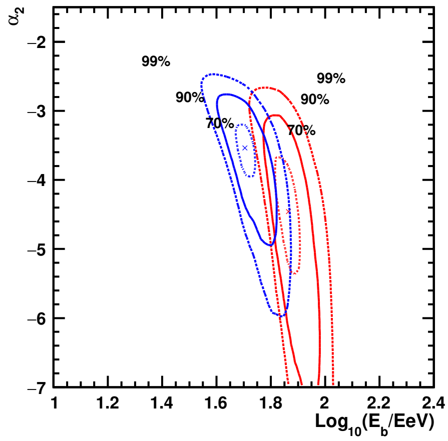


**Figure 6:** Contour of $\delta \log L$ and best fit parameter pair. The lines are the same with Fig.5.

latest data are now under calculation.

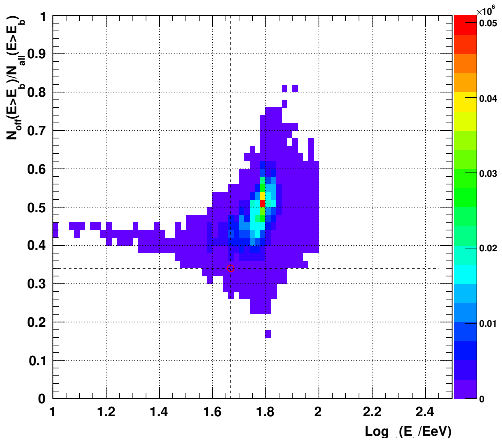


**Figure 7:** Distribution of $N_{off}(E > E_b)/N_{all}(E > E_b)$ vs $\log_{10}(E_b/EeV)$ obtained from random resampling.

## 3. Summary

We have searched for anisotropy correlated with matter distribution in the energy spectra of cosmic rays with energies above $10^{19}$eV obtained by TA surface detectors. We performed the same analysis as we did for the previous 5 years of data, with the addition of 12 years of data. As shown in Tables 1,2, the tendency for a lower break energy and smaller event fraction in the Off source region are present in both the five and 12 year data.

**Table 3:** Number of cases at uniform spectrum simulation. Chance probability to obtain larger deviation from estimation in this simulation is 6.2× $10^{-4}$.

| area | Case | Fraction |
|---|---|---|
| $E_b > 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.337$ | 45031 | 0.9008 |
| $E_b > 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.337$ | 4606 | 0.0921 |
| $E_b < 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.337$ | 31 | 0.00062 ± 0.00011 |
| $E_b < 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.337$ | 352 | 0.00704 |

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