PROCEEDINGS OF SCIENCE

Anisotropy search in Energy distribution in Northern hemisphere using Telescope Array Surface Detector data

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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. In the region of highest energies, the shape of cosmic ray energy spectrum may contain information on the source density distribution and chemical composition. In this study, using events observed with Telescope Array surface detector, we search for directional differences in the shape of energy spectrum. Observed cosmic ray energy spectra are compared between sky areas that have larger density of nearby objects, such as the super-galactic plane, and others that do not. If there were a direction that contains a nearby source or events of heavier composition at higher energies, there should be an enhancement of the probability to observe coincidences of arrival direction between high energy and low energy events. Based on this idea, we searched for such an enhancement. We report on results of those studies.

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1. Introduction

The Telescope Array experiment found "Hot Spot" using angular window of 20° [1] in their high energy data set(Energy $>$ 57EeV). The angular size which is expected proton primary particles was rather small [2, 3]. This may imply particles at high energy end are heavier particles than proton. On the contrary, AGASA experiment [4] reported a small-scale clustering above 4×10^{19} eV in their data [5]. It also pointed that HiRes experiment [6] recorded an event which is coincident with one of those clustering. In the experimental results, the average mass number of UHECR is not clear at very high energy end because of lack of statistics. And also uncertainty of interaction model may give additional uncertainty of measured mass number [7, 8]. Expected angular size of anisotropy of UHECR from single source is not known because of the uncertainty of chemical composition. In this report, we discuss anisotropy in spectrum [9] and comparison with simple model of cosmic ray. And directional correlation between high energy event with E>57 EeV and lower energy events with 19 EeV < E <57 EeV.

2. Experiment and analysis

Telescope Array(TA) experiment [10] is a hybrid detector which observe cosmic rays with 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 grid to have totally 670 km^2 of area for detecting UHECR [11]. The energy of observed cosmic ray is calibrated with fluorescence detectors observing the sky above the surface detector array. The operation of the surface detector was started from 2008. A duty cycle of the surface detector observation is 95% on average every year.

In this analysis, cosmic ray events with energy E$> 10^{19.0}$ eV observed in the period May 2008 to May 2013 are used. The period is the first 5 year of operation of surface array of TA. The resolution of reconstructed energy is estimated by Monte Carlo simulation. The estimated energy resolution is about 20% and angular resolution is 2° [10, 12]. Efficiency to trigger arrival particles is estimated to be 100% for the shower with E $> 10^{19}$ eV at the zenith angle $< 55°$. The zenith angle distribution of exposure for latitude lower than $|30°|$ from super galactic plane and that larger than $|30°|$ are identical at a few percent level.

2.1 Comparison of energy distributions

It is expected that cosmic ray spectrum will show different shape of attenuation depending on distance from source and composition at origin. So consequently, by comparing spectrum shape and simulated energy spectrum it is possible to constrain parameters of assumptions in simulation such as composition, spectrum index and evolution parameter [13]. Figure.1 shows objects in 2MRS catalog [14]. It shows that more objects closer to the earth exist near the Super-Galactic Plane(SGP). First, a comparison between energy distributions observed and expectation from a simple model was done. Figure.2 shows three different energy distribution each correspond to the one obtained from entire sky, On source area (Super-Galactic latitude < $|30°|$) and Off source area (Super-Galactic latitude > $|30°|$) respectively. The black line in Figure. 2 shows best fit broken power law which is expressed in formula 2.1. Here E_o is 1EeV. C_0 represents normalization constant promotional to total number of events. $\alpha_{1,2}$ represents spectrum index at lower energy and higher energy than E_b.

$$\frac{\Delta N(E)}{\Delta \log_{10}\left(\frac{E}{E_o}\right)} = C_0\left(\varepsilon\left(E,E_b\right)\left(\frac{E}{E_o}\right)^{-\alpha_1} + \left(1-\varepsilon\left(E,E_b\right)\right)\left(\frac{E_b}{E_o}\right)^{-\alpha_1}\left(\frac{E}{E_o}\right)^{-\alpha_2}\right) \tag{2.1}$$

$$\varepsilon(E,E_b) = \{1 : (E < E_b)\ ,0 : (E > E_b) \tag{2.2}$$

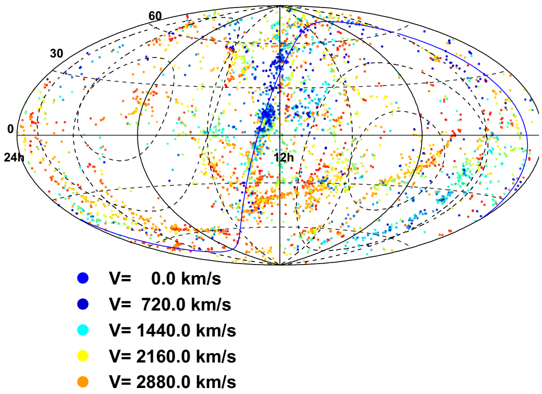

Figure 1: Nearby galaxies listed in 2MRS catalog [14] plotted in equatorial coordinate

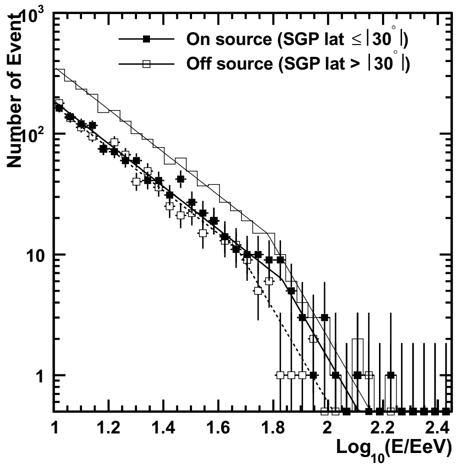

Figure 2: The zenith angle distribution while observing On source area and off source area is plotted

Table.1 shows summarized best fit parameters and errors. The chance probability was estimated by a simulation which assumes both distribution is coming from population which observed in entire exposure.The simulation were done by shuffling entire event in each energy bin to On source and Off source distribution according to the fraction of exposure binomial. At each trial of simulation, we obtain random distribution coming from same population, and did same evaluation for distribution difference. Here we take break energy E_b at off source and fraction of number of event above the break energy at off source. Table.3 shows chance probability to obtain each case. The chance probability for observed value is $\sim 6.2\times10^{-4}$. The observed energy distribution is significantly differ between SGP direction and other.

A simple simulation were performed using a propagation simulation code CRPropa 2.2.0.4 [15]. In the simulation source distribution along the distance are assumed to be proportional to object density of 2MRS catalog [14] using the method to calculate density profile of object employed at article [16]. Figure. 4 display results simulated energy distribution of cosmic ray. At the figure, source spectrum index is set -2.2 and evolution parameter along red shift is set as 7. These param-

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 1: Parameters of the best fit broken power law in the SGP case.

eter are taken from [13]. Qualitatively, observed feature of the difference between On source and Off source does not show significant disagreement with the one expected from employed model.

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

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

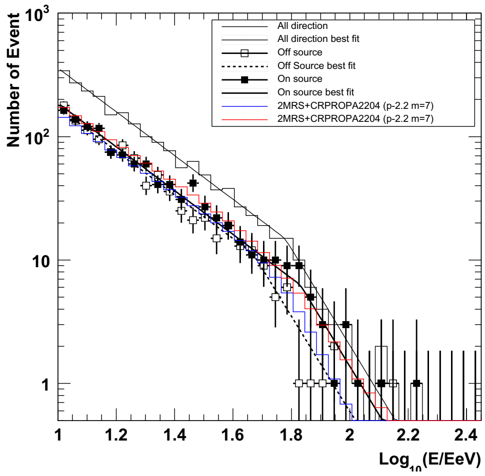

Figure 4: Comparison between expected flux in case of proton with power index -2.2 , evolution factor 7, with 2MRS density profile.

2.2 Search of clustering of lower energy events

When there is more contamination of heavier particles above energy of 57 EeV, there should be heavier particles those have same rigidity with proton with lower energy. If such pair of heavier particle with higher energy and proton primary with lower energy are generated by same source, in case the rigidity is effectively same, they tend to create clustering within small angular radius in our data. To see this, a search of clustering of lower energy event around higher energy events with E>57 EeV was done using 5 year data set. In the analysis, events were grouped into high energy events and lower energy events using energy. Events with energy > 57 EeV were categorized as high energy events. For lower energy event, threshold was decided as following. If heavier particle with charge number Z exist at $E > 57$ EeV, corresponding energy of proton with same rigidity would be 1/Z of that. When threshold of higher energy event was set to 57 EeV, there are corresponding lower energy threshold with step of Z (= 2, 3, 4,,). In this analysis, we took 19 EeV as lower threshold. Because our energy resolution start marge between steps Z=3 (19EeV) and Z=4 (14.25 EeV). So lower threshold was taken as E>19 EeV. The opening angle was taken 3.0°, 6.0° and 9.0°. To see excess of number of lower energy event, lower energy events are integrated with opening angle. Then local significance at each direction were calculated in the same way used in [1]. Figure.5 shows the distribution of high energy events and calculated significance of lower energy event. Arrival direction of observed high energy event are displayed with $\star$ and calculated significance are displayed with color chart.

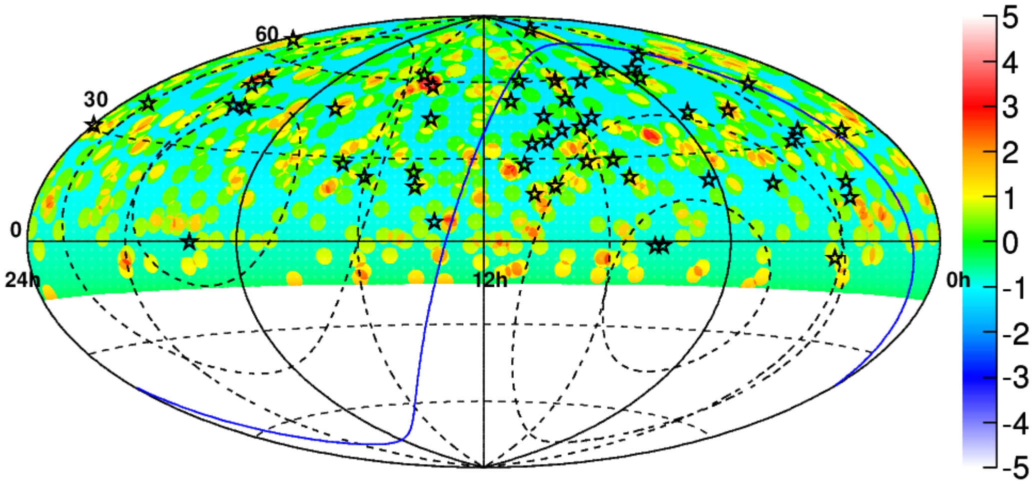

Figure 5: Significance map of clustering of lower energy cosmic rays and arrival direction of higher energy cosmic ray. Observed direction of high energy event are displayed with $\star$ and calculated significance were displayed with color chart.

Figure.6 shows observed distribution of significance proportional to solid angle within 3° from high energy event. Observed maximum local significance within 3° from one of high energy event was 4.95 sigma. Solid line in Figure.6 shows expected distribution in case high energy events and lower energy events are not correlated. Additional dashed lines in the same figure display deviation of 2σ and 3σ level from expectation. The expected distribution was calculated by Monte Carlo simulation which shuffle direction of observed lower energy events. In the Monte Carlo simulation, direction of high energy event was kept same as observed. It is seen the number of solid angle tend to reach 3σ at higher significance. Figure.7 shows number of appearance of larger significance than observed highest significance within 3° from high energy event. In 10^5 times of trial by Monte Carlo simulation, there were 963 cases which exceed local significance value 4.95σ and 76 cases were observed near high energy event. Preliminary estimation of chance probability for observed clustering near highest event is 7.6×10^{-4}. To see angular size of this, same analysis are repeated with larger opening angle 6° and 9°. Figure.8 and Figure 9 shows significance map displayed in a same way with Figure.5 in case size of opening angle are 6° and 9° respectively. Preliminary result of the calculated chance probability for observed highest significance for each case are 1.2×10^{-2} and 8.6×10^{-2} respectively.

3. Summary

We showed energy distributions from different sky areas and a comparison with simple simulation using a propagation simulation code. Qualitatively, observed feature of the difference between

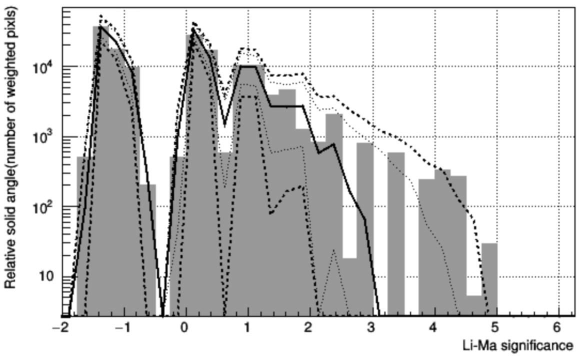

Figure 6: Preliminary result of distribution of significance near high energy event. Observed maximum local significance was 4.95 sigma within 3° from one of high energy event. Colored histogram shows distribution of observed relative solid angle with the significance. Solid lines show expectation in case high energy events and lower energy events are not correlated.

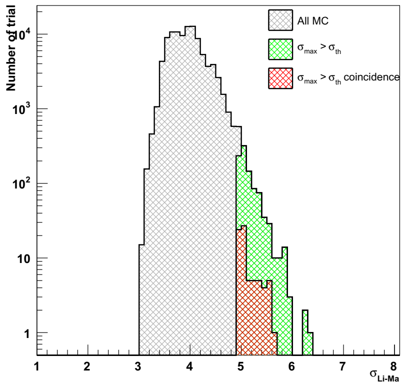

Figure 7: Monte Carlo simulation to obtain larger maximum significance within 3° of arrival direction of higher energy cosmic ray.

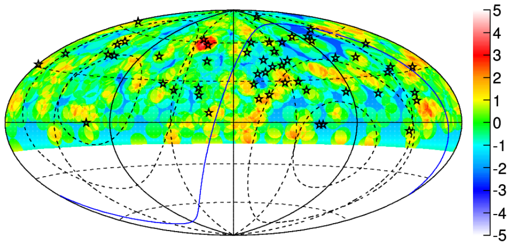

Figure 8: Same with Figure. 5 with 6° of integration area for lower energy events.

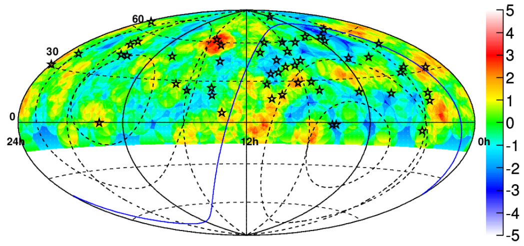

Figure 9: Same with Figure. 5 with 9° of integration area for lower energy events.

On source and Off source does not show significant disagreement with the one expected from employed model. A quantitative comparison with the theoretical predictions would require a more statistics at high energy. Also, we searched small clustering of lower energy events at near from observed direction of high energy events. The clustering is expected in case heavier particles those have same rigidity with proton with lower energy. We analyzed data by categorize data into high energy event (E>57EeV) and low energy event (57 EeV > E > 19 EeV). By comparing significance distribution with null hypothesis, at least in case using opening angle as 3°, we saw a possible tendency of larger excess of low energy event near high energy event. In case of using wider opening angle,6° and 9°, result did not show significant tendency. This preliminary result and further check on 5 year data set should give optimum hypothesis. We would like to apply it for data set from 10 years of observation.

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