

Examination of Xmax anisotropy for the next generation Ultra-high energy cosmic rays observations

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Abstract. The estimation of mass composition ultra-high energy cosmic rays is essential to understand their origin and generation mechanism. Recent experiments are expected to discover anisotropy of mass composition in ultra-high energy cosmic rays. Anisotropy of mass composition using Xmax is currently being performed, but the problem is that the statistics of cosmic rays with measured Xmax is very small. For the next generation experiments, it is important to know how much statistics can be accumulated to find Xmax anisotropy. Therefore, in this analysis, we examine Xmax anisotropic search in ultra-high energy cosmic rays by simulating a cosmic ray air showers under various conditions such as energy spectrum and mass composition.

1 introduction

Ultra-high energy cosmic rays(UHECR) have been observed since the Akeno Air Shower Observatory[1] started operation in 1979, and the Fly's Eye experiment[2] in 1981, which established a method for measuring air showers with an atmospheric fluorescence telescope. Since then, various experiments such as the Telescope Array (TA)[3] and the Pierre Auger Observatory[4] have been conducted to observe and study cosmic rays. Cosmic rays have been observed over a wide energy range from 10^8 eV to 10^{20} eV. In particular, cosmic rays with energies higher than 10^{18} eV are called ultra-high energy cosmic rays. The question of where and how the ultra-high energy cosmic rays with energies as high as 10^{20} eV are produced is one of the problems in cosmic ray physics. To solve this question, observational experiments on cosmic rays have been conducted to measure the flux, mass composition, and arrival direction of cosmic rays. Recent experiments have shown signs of anisotropy in the vicinity of HotSpot, WarmSpot, and Supergalactic plane[5]. In addition to energy and arrival direction, mass composition anisotropy analyses using Xmax is now being performed and is expected to be a promising method. However, in the ultra-high energy region, there is a problem that the statistics are very small due to the small arrival frequency and limited duty cycle of the fluorescence technique that can directly measure Xmax. To increase the statistics, it is expected that the next generation of cosmic ray observational experiments will be performed a much larger scale. Therefore, it is important for the planning of the next generation of experiments to investigate what we can learn about the future physics of cosmic rays with a certain amount of statistics. Here, we have focused on the anisotropy analysis of mass composition. In this work, we investigate how much statistics is

required for Xmax anisotropy to appear in simulations under different conditions of mass composition and energy spectrum.

2 Data Set

The following is a detailed description of the data set used for the simulations. The longitudinal evolution of air showers was generated by a Monte Carlo simulation using Corsika.[6] A detailed description of the data obtained from the simulations is given as follows.

- Primary composition : Proton, He, CNO(1:1:1), Si, Iron
- Interaction model : EPOS-LHC
- Log(E/eV) : 19.7-19.8, 19.8-19.9, 19.9-20.0
(Generated continuously inside each energy bin)
- Zenith angle : 0 - 65 degrees
- Thinning factor : -4

For each combination of energy and mass composition, 1000 air shower events were generated using EPOS-LHC as hadronic interaction model.

3 Analysis

In this work, we developed a new analytical method. The outline of this analysis is to compare the Xmax distributions of two regions by randomly selecting assumed regions, energies, and mass compositions according to probabilities, and to verify how much statistics is required for the Xmax distributions of the two regions to be significantly different. Here, two regions are assumed : one is the TA HotSpot region[?] [?] and the other is the Background region. Including assumed energy and mass compositions, the analysis procedure is described as follows:

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1. Select two regions (HotSpot, Background) to compare with probability as described in Subsection 3.2
2. Randomly select to follow the assumed energy spectrum and mass composition ratios in the selected region
3. Perform KS test on the two regions for a total of every 10 events.
4. Check the p-value obtained by the KS test and the change in the number of events.

3.1 assumption of energy and composition

The parameters assumed in the simulation are the region, energy, and mass composition. Since we have already assumed the region, we must now assume the energy spectrum and mass composition ratios. In the following, we will explain the details of the assumptions for the energy spectrum and the mass composition ratios.

3.1.1 energy

Figure 1[7] is the result of the energy spectrum obtained by TA experiment. In this analysis, the energy spectrum in the HotSpot region is the same as the energy spectrum in the Background region. Then, the event flux ratio for each energy is calculated based on this spectrum. As seen in Figure 1, the spectrum consists of power spectra for each energy region, and for energies above $3 \times 10^{17} \text{eV}$, the function is expressed as in Equation 1.

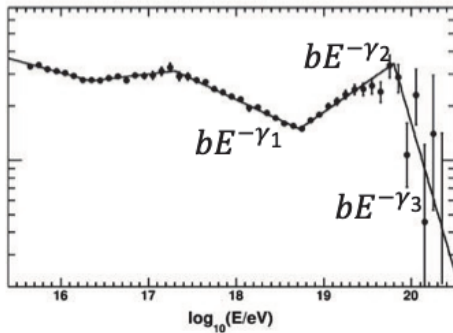


Figure 1: The energy spectrum obtained from the TA experiment[7]

$$\begin{aligned}
 & E^{-\gamma_1} (E < E_{ankle}) \\
 J(E) = & E^{-\gamma_2} (E_{ankle} < E < E_{break}) \\
 & E^{-\gamma_3} (E < E_{ankle})
 \end{aligned} \quad (1)$$

Based on the above equation and parameters, the energy region from $10^{19.7} \text{eV}$ to $10^{20.0} \text{eV}$ is divided into three parts and the flux ratio in each region is calculated (Table 2).

Table 1: Values of the broken power-law fit parameters for the TA energy spectrum above $3 \times 10^{17} \text{eV}$ [7]

TA spectrum parameters				
γ_1	γ_2	γ_3	$E_{ankle}[\text{EeV}]$	$E_{break}[\text{EeV}]$
3.226 ± 0.007	2.66 ± 0.02	4.7 ± 0.6	5.2 ± 0.2	60 ± 7

Table 2: Ratios of fluxes in three energy regions

Ratios of fluxes	
$10^{19.7 \sim 19.8} [\text{eV}]$	0.65
$10^{19.8 \sim 19.9} [\text{eV}]$	0.26
$10^{19.9 \sim 20.0} [\text{eV}]$	0.09

3.1.2 composition

Figure 2 shows the energy densities together with the fit for various mass compositions obtained from the Auger experiment. In the present analysis, we calculate the mass composition ratios in each energy region using Figure 2[8]. The Background mass composition ratios are taken from Figure 2. Table 3 lists the hotspot events for the first five-year period. The number of observed is 19, and the number of expected is 4.49, meaning that 14.51 more events are observed than expected. In other words, more events were observed in the HotSpot region than expected, so excess events must be taken into account. When calculating composition of HotSpot region, 4.49 events are calculated with mixed composition 14.51 events are calculated with pure proton.



Figure 2: Energy densities with the fit for various mass compositions obtained from the Auger experiment[8]

The calculated mass composition ratios are shown in Table 4.

3.2 Comparison of Xmax distributions between Background and HotSpot

Assuming the energy spectra and composition ratios inside and outside the HotSpot, we randomly extract Xmax

Table 3: Numbers of events in the Background and HotSpot regions in the first 5 years of the TA data.

Number of observed	number of expectation as background	number of excess
19	4.49	14.51

Table 4: Composition ratios in three energy regions for the Background and HotSpot

Proton : CNO : Si : Iron (Background)	
$10^{19.7\sim 19.8}[eV]$	0.0 : 4.4 : 4.4 : 1.2
$10^{19.8\sim 19.9}[eV]$	0.0 : 2.6 : 5.4 : 2.0
$10^{19.9\sim 20.0}[eV]$	0.0 : 1.6 : 5.2 : 3.2
Proton : CNO : Si : Iron (HotSpot)	
$10^{19.7\sim 19.8}[eV]$	7.6 : 1.1 : 1.1 : 0.2
$10^{19.8\sim 19.9}[eV]$	7.6 : 0.6 : 1.3 : 0.5
$10^{19.9\sim 20.0}[eV]$	7.6 : 0.4 : 1.2 : 0.8

from the data set according to the determined probabilities. In this analysis, we focus on the number of events where Xmax anisotropy appears. To examine how much the Xmax distributions in the two regions are statistically significantly separated, we need to compare the Xmax distributions between the HotSpot region and the Background region for each event obtained according to the assumed energy spectrum and mass composition mixing ratios. The observation of the TA experiment shows that there are 72 events above 57 EeV in the last 5 years(2008 2013), of which 19 events are in the HotSpot and 53 events are in the Background. In the following we explain the process of retrieving events and comparing their distributions.

First, two regions (HotSpot or Background), three energy regions, and five mass compositions are randomly selected with probability according to the assumption, and Xmax is randomly obtained from the data set. Figure3 shows the Xmax distributions when a total of 50 events are obtained in the two regions, and the p-value is calculated using KS test every 10 events in total in the Xmax distributions in the HotSpot and Background regions. The test is continued by obtaining events until the p-value obtained from the test exceeds 3σ . Figure4 is the result. As the number of events increases, the p-value of the test result becomes smaller, and when the number of events exceeds a certain number, the p-value falls below the confidence level, indicating that the Xmax distributions of the two regions is significantly separated. In other words, the statistic at the point where 3σ is exceeded is the statistic necessary for the distributions in the two regions to be significantly separated. However, it is also possible that the results shown in Figure4 are obtained by chance, since the events in this simulation are obtained randomly according to the probability. Therefore, it is necessary to con-

sider a new evaluation method. Next, we describe the new method.

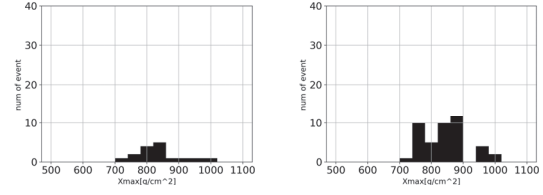


Figure 3: Xmax distributions at a total of 50 events. Left panel shows a distribution of HotSpot .Right panel shows a distribution of Background

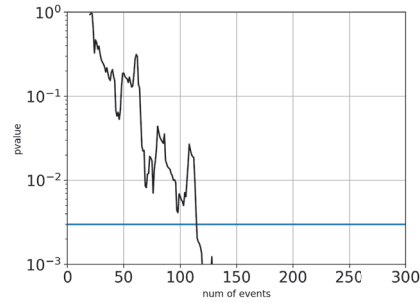


Figure 4: P-value from the comparison between the HotSpot and Background Xmax distributions every 10 events

3.3 Number of events required to significantly separate the Xmax distributions of the two regions

In this section, to account for the possibility that the results in Figure4 could have occurred by chance, the sequence of acquisition events is repeated 10,000 times until the p-value obtained by the test exceeds 3σ . This is equivalent to finding the number of Xmax observations required for a sufficient difference in the Xmax distribution to appear in 10,000 experiments. Then, from the results of 10,000 times, we estimate the number of observations required to detect a sufficient difference in the Xmax distribution of 3σ (99.7%).

Figure5 shows the results of 10,000 times, and all 10,000 results are different because the events are randomly obtained and compared by probability. These results are used for evaluation.

As the number of events increases, the p-value decreases and exceeds 3σ at a certain number of events. The number of experiments with p-values exceeding 3σ as the number of events also increases. Figure 6 shows the distribution of p-value at 50 events obtained from the simulation. Figure 7 show the distributions for 100 and 150 events, respectively.

Since the number of experiments exceeding 3σ is expected to increase as the number of events increases, the

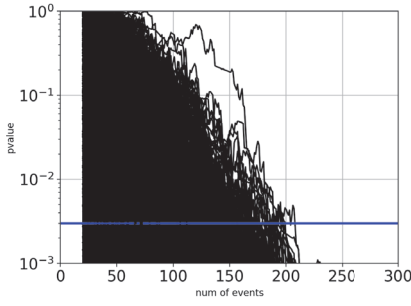


Figure 5: p-value obtained by comparing the HotSpot and Background Xmax distributions for every 10 events for 10,000 results

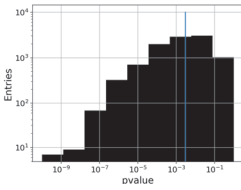


Figure 6: The distributions of p-value at 50 events

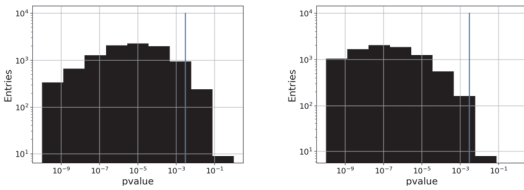


Figure 7: The distributions of p-value. Left figure is for 120 events. Right figure is for 150 event.

number of experiments exceeding 3σ for a given number of events is 9970 (99.7 %) out of 10000. In this case, the number of events is assumed to be the statistics required to find the Xmax anisotropy. Figure 8 counts the number of experiments exceeding 3σ for each number of events. Under the conditions of EPOS-LHC for the hadron interactions model and proton for excess particles in the HotSpot, the Xmax distributions of the HotSpot and Background are significantly separated at about 165 events.

In the previous analysis, the excess particles in the HotSpot were protons. Moreover, we analyzed when the excess particles were He, CNO, Si and Iron particles, and the energy range was changed. we calculated some energy range with Figure1 and equation1. Figure 9 shows the results. Table 5 summarizes the results from Figure 9. The statistics required to observe the Xmax anisotropy are, in decreasing order, Proton, He, Fe, CNO, and Si. Since there is no proton in the Background mass composition ratio, the excess particle in the HotSpot region are considered to separate the fastest in the case of proton.

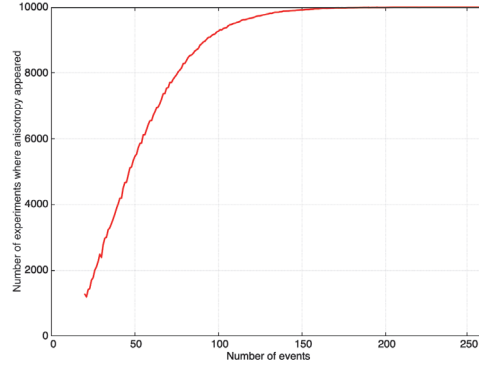


Figure 8: Result of the number of experiments when anisotropy appears as a function of the number of events

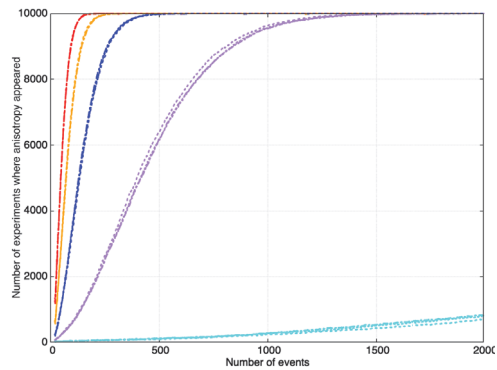


Figure 9: The number of experiments when anisotropy appears as a function of the number of events. The solid line shows the median value of the energy spectrum parameters, and plotted line shows Upper and lower limits of energy spectrum error bars. Proton, He, CNO, Si, Iron are indicated as Red, Orange, Purple, Cyan, Blue.

Table 5: The number of event which required to find Xmax anisotropy. The solid line shows the median value of the energy spectrum parameters, and plotted line shows Upper and lower limits of energy spectrum error bars. Proton, He, CNO, Si, Iron are indicated as Red, Orange, Purple, Cyan, Blue.

EPOS-LHC	
Proton	166_{-5}^{+1}
He	251_{-6}^{+5}
CNO	1469_{-40}^{+20}
Si	10000 <i>and more</i>
Iron	481_{-11}^{+3}

4 Conclusion

Recent observations of cosmic rays with TA experiment show signs of anisotropy due to energy in the HotSpot region, WarmSpot, and supergalactic plane. Along with energy and arrival direction analysis, anisotropy analysis of mass composition using Xmax is also expected,

but the statistics are very limited due to the duty cycle of the telescopes that can detect X_{\max} . In this examine X_{\max} anisotropic search in ultra-high energy cosmic rays by simulating cosmic ray under various conditions, energy spectrum and mass composition. And we estimate statistics required to find out the difference on the X_{\max} distributions are evaluated by the simulation with some assumptions.

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