

A Study on Anisotropy in the Arrival Directions of Ultra-High-Energy Cosmic Rays Observed by Pierre Auger Observatory

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We study the anisotropy in the arrival directions of PAO UHECRs, using the point source correlational angular distance distribution. The result shows that the anisotropy is characterized by one prominent excess region and one void region. The excess region is located near the Centaurus A direction, supporting that the Centaurus A is a promising UHECR source. The void region near the south pole direction may be used to limit the diffuse isotropic background contribution.

PACS numbers: 98.70.Sa

Keywords: ultra high energy cosmic rays, anisotropy, Centaurus A

arXiv:1212.6479v1 [astro-ph.HE] 28 Dec 2012

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I. INTRODUCTION

The cosmic ray with energy of order of 10^{20} eV was first reported in almost 50 years ago [1]. Then, the observation of cosmic microwave background radiation followed [2]. Soon after, Greisen [3], Zatsepin and Kuzmin [4] pointed out that the interaction with the cosmic microwave background would cause the energy loss and limit the distance that such high energy cosmic rays could travel. This would result in the suppression in the cosmic ray energy spectrum above the so called GZK cutoff $E_{\text{GZK}} \sim 4 \times 10^{19}$ eV, if the sources are distributed over the whole universe. If this suppression is true, as indicated by recent observations [5–7], it implies that UHECR with energies above the GZK cutoff mostly come from relatively close extragalactic sources within the GZK radius $r_{\text{GZK}} \sim 100$ Mpc. One consequence of this would be anisotropy in the arrival directions of ultra-high-energy cosmic rays (UHECR), since the matter within the GZK radius is distributed inhomogeneously and the UHECR sources are more or less correlated with the matter distribution. Therefore, the existence of anisotropy is an important clue for tracing the origin of UHECR.

Searches for anisotropy in the UHECR arrival directions have been done by using many different methods. For the PAO data, the anisotropy manifested itself as a correlation between the UHECR arrival directions and the locations of active galactic nuclei (AGN) [8, 9]. When we extend the correlation study to the galaxy distribution, the conclusion is less clear than in the AGN case [10]. Besides, instead of being based on the astrophysical objects, the anisotropy search based on the auto-clustering did not provide a strong evidence of anisotropy [11].

Surely the result of anisotropy study depends on methodology. We need a method appropriate for the purpose we consider and the amount of data we have. One serious huddle in the anisotropy search in the UHECR arrival directions is that cosmic rays can be strongly affected by the intergalactic magnetic fields. UHECR have such high energy that the intergalactic magnetic fields could not completely erase the anisotropy arising from the inhomogeneous distribution of sources. However, the auto-clustering at small angles could be significantly weakened. In the presence of such magnetic fields, the better way to see the clustering due to the strong point source would be to examine the point-wise clustering up to large angles. The existence of a point source would manifest itself through the local clustering of observed UHECRs about the location of the source. This is nothing but a general principle for finding point sources of various bands of radiation in astronomy. In the case of UHECR, what is different from other astronomical particles is that the spreading could be much larger and the number of data is small.

This paper reports this pointwise clustering test for the arrival directions of UHECR observed by Pierre Auger Observatory (PAO), aiming for both the anisotropy study and the point source search. To see whether the local clusterings exist in the observed PAO data, we sweep the whole sky covered by the PAO exposure by taking each point as the reference point for the clustering of arrival directions. We take the angular distance distribution of UHECRs about the reference point and compare it with the one expected from the isotropic distribution. We calculate the p-value by applying the Kuiper test on the angular distance distribution. The small p-value implies the departure from isotropy about the reference point. The departure from the isotropy can arise either from the excess (local clustering) or the deficit (local void). In Sec. 2, we describe the detail of statistical method we use, including the criterion for this excess/deficit decision based on the Kuiper test. In Sec. 3, we present the results for the PAO UHECR arrival directions, characterizing anisotropy by

one strong excess region and one void region. We discuss the implications of the results and conclude in Sec. 4.

II. ANISOTROPY STUDY USING THE SINGLE SOURCE CADD METHOD

There are many ways to test the isotropy of the spherical data. First, we may check the multipole moments. We can also use the auto-correlation of arrival directions, which is good for checking if there are small scale clusterings or some regularities.

Here we use the test method suitable for hunting for the point sources of UHECR. We take any one point on the sphere as a reference point and examine the distribution of arrival directions about that point. The simple way is to look at the angular distance distribution of arrival directions from the reference point. In Refs. [12, 13], we developed the simple comparison method for the UHECR arrival direction distributions, where the two-dimensional UHECR arrival direction distributions on the sphere is reduced to one-dimensional probability distributions of some sort, so that they can be compared by using the standard Kolmogorov-Smirnov (KS) test or its variants. For the correlation test, we adopted the reduction methods called the correlational angular distance distribution (CADD). The method used in this paper is simply the special case of CADD, where the reference point is taken as if it is a single source. When averaged over the all point sources, this is similar to Ripley's K function, a well-known second-order summary characteristic for the spatial pattern. We do not take the average as we focus on the local clustering, not on the overall clustering characteristic. Here we present briefly the basic ideas of the reduction method and how to calculate the p-value for the isotropy.

The correlational angular distance distribution is the probability distribution of the angular distances of all pairs of UHECR arrival directions and the point source directions. As we consider the reference point as a single source, CADD is just the probability distribution of the angular distances of UHECR arrival directions from the reference point: $\theta_i \equiv \cos^{-1}(\hat{\mathbf{r}}_i \cdot \hat{\mathbf{R}})$, where $\hat{\mathbf{r}}_i$ ($i = 1, \dots, N$) are the UHECR arrival directions and $\hat{\mathbf{R}}$ is the reference direction. For the comparison of CADD obtained from the data and that from the isotropic distribution, we can apply KS test or its variants such as Kuiper test. In this analysis, we use Kuiper test because it seems most suitable for our purpose and the probability function of its statistic is available in analytic form. The Kuiper test is based on the cumulative probability distribution (CPD), $S_N(x) = \int^x p(x')dx'$ and the Kuiper statistic D_K is the sum of maximum difference above and below two CPDs,

$$D_K = D_{K+} + D_{K-}, \quad (1)$$

where

$$D_{K+} = \max_x [S_{N_1}(x) - S_{N_2}(x)], \quad D_{K-} = \max_x [S_{N_2}(x) - S_{N_1}(x)]. \quad (2)$$

From the KP statistic D_K , the probability that CADD of the observed data is obtained from the model under consideration can be estimated using the Monte-Carlo simulations in general. When the data in the distribution are all independently sampled, as in our case, the following approximate probability formula is available:

$$P(D_{KP}|N_e) = Q_{KP}([\sqrt{N_e} + 0.155 + 0.24/\sqrt{N_e}]D_{KP}), \quad (3)$$

where $Q_{KP}(\lambda) = 2 \sum_{j=1}^{\infty} (4j^2\lambda^2 - 1)e^{-2j^2\lambda^2}$ and $N_e = N_1N_2/(N_1 + N_2)$ is the effective number of data. Now, $N_1 = N_O$, the number of observed UHECR data and $N_2 = N_S$, the number

of mock UHECR data obtained from the isotropic distribution. We can make the expected distribution more accurate by increasing the number of mock data N_S . In the limit $N_S \rightarrow \infty$, the effective number of data is simply $N_e = N_O$.

For a given reference point, we obtain two single point CADDs to be compared, one from the observed PAO data and the other expected from the isotropic distribution. Then we calculate the p-value using the formula (3). The small p-value indicates that the distribution of arrival directions in view of the given reference point significantly differs from the isotropic distribution. The departure from isotropy can be either the local excess or the local deficit of observed UHECR around the reference point compared to the isotropic distribution. For small p-value, to decide whether it is the excess or the deficit, we consider the following: The Kuiper test uses the maximum differences of the observed distribution above and below the expected distribution, D_{K+} and D_{K-} . Let the angular distances at which D_{K+} and D_{K-} are attained be θ_+ and θ_- , respectively. Then, the order of the angular values θ_+ and θ_- can be used for this purpose. If $\theta_+ < \theta_-$, it is probably the excess. If $\theta_+ > \theta_-$, it is probably the deficit. Of course, there can be a subtlety that small excess or deficit very near the reference point can be missed. But, this simple rule could catch the overall behavior correctly in most cases.

III. RESULTS FOR UHECRS OBSERVED BY PAO

We use the UHECR data set released in 2010 by PAO [8]. It contains 69 UHECR with energy higher than 5.5×10^{19} eV. Their arrival directions are shown as black dots in Fig. 2. The PAO site has the latitude $\lambda = -35.20^\circ$ and the zenith angle cut of the data is $\theta_m = 60^\circ$. We use the geometric exposure function, which is known to work well for the cosmic rays with energy higher than the GZK cutoff.

We sweep the whole sky covered by the PAO exposure, by taking each point as the reference point for the reduction of the arrival direction distribution to single point CADD. For illustration of our method, we show in Fig. 1 the cases of two reference directions whose p-values are smallest among excess regions and deficit regions. The maximal excess point is ($\alpha = 192.75^\circ$, $\delta = -38.77^\circ$) and the maximal deficit point is ($\alpha = 81.69^\circ$, $\delta = -67.90^\circ$), which are marked by the + symbols in Fig. 2. The left panels show the CADD with angular bin size of 10° . Compared to the CADD of isotropic background (green dashed lines), the excess and the deficit of the PAO data (black solid lines) at small angles are clearly seen. The right panels show the corresponding CPD, to which we apply the Kuiper test and obtain the p-values $P_{\text{excess},\text{min}} = 2.0 \times 10^{-4}$ and $P_{\text{deficit},\text{min}} = 1.2 \times 10^{-3}$, respectively. The vertical bars represent the sizes of D_{K+} , D_{K-} and the angular distances θ_+ , θ_- at which they are attained. For the excess at small angles, we have $\theta_+ < \theta_-$. For the deficit at small angles, the order is reversed. It confirms that we can tell the excess region and the deficit region from the order of θ_+ and θ_- . However, one caveat is in order. Because θ_+ and θ_- are determined from the whole distribution over small to large angles, sometimes small clustering at small angles can be overlooked. An example can be found around $\alpha = 90^\circ$, $\delta = -15^\circ$ region. It seems that there is a small clustering there, but the region is classified into the deficit region due to the stronger deficit at middle angles.

In Fig. 2, we show our main result, the map of p-values obtained by the single source CADD method for the PAO UHECR data. The black dots are the arrival directions of PAO data and graded colors represent the p-value bands as indicated in the p-value scale bar. Our criterion for the excess or deficit region is that the p-value of that region is smaller

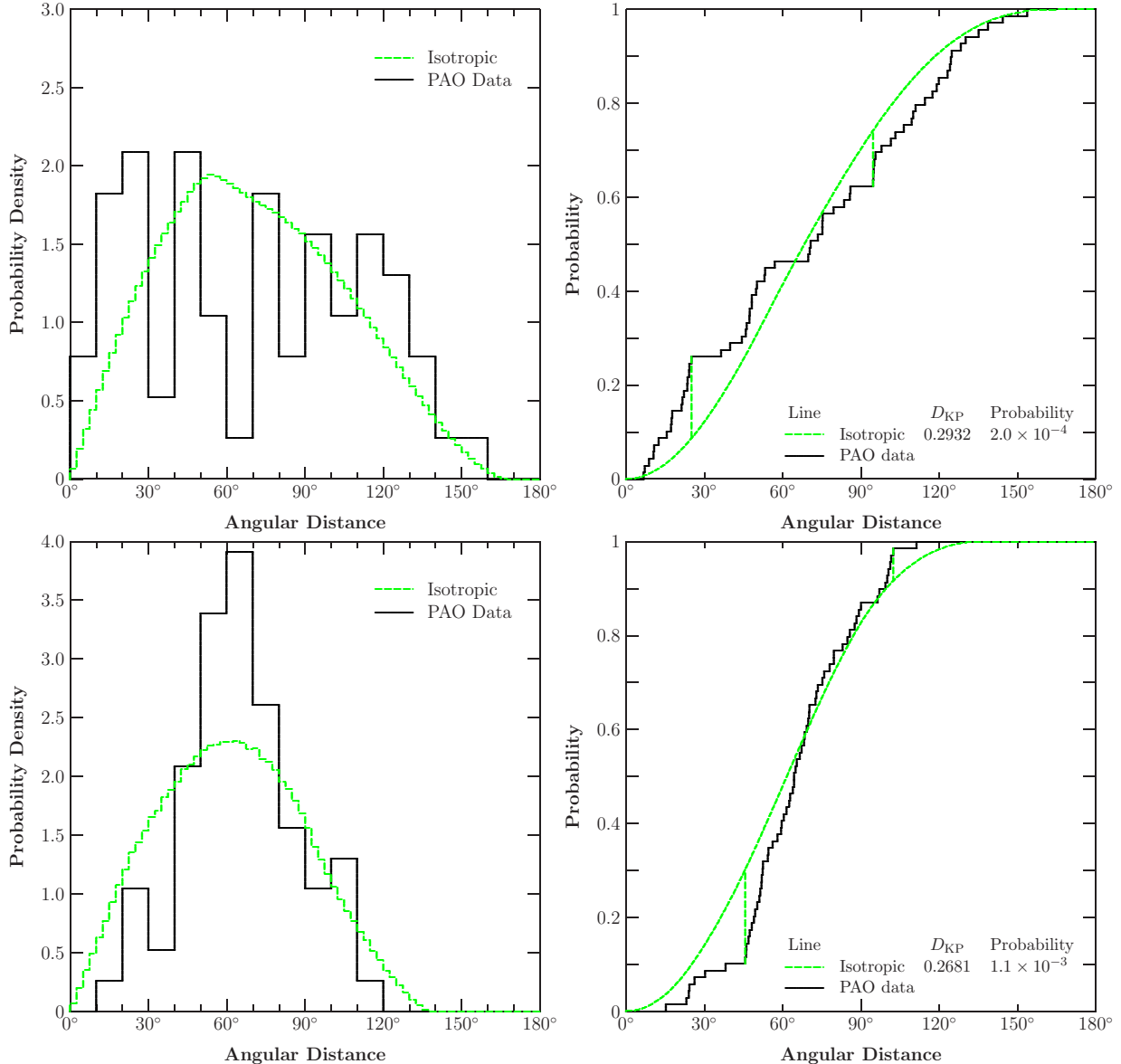


FIG. 1. Single point CADD and its CPD of the PAO data compared to those of the isotropic distribution for two illustrative reference points. The upper panels are for the maximal excess point ($\alpha = 192.75^\circ$, $\delta = -38.77^\circ$), and the lower panels are for the maximal deficit point ($\alpha = 81.69^\circ$, $\delta = -67.90^\circ$). The vertical bars in CPD represent the sizes of D_{K+} , D_{K-} and the angular distances θ_+ , θ_- at which they are attained.

than 0.0455. To those regions we apply the excess/deficit criterion explained in the previous section to further classify them into the excess or the deficit regions. They are depicted in red color or in blue color for distinction.

An overall feature is that we have one large excess region and one large void region. The large excess region is centered around the location of Centaurus A ($\alpha = 201.37^\circ$, $\delta = -43.02^\circ$, marked by the \times symbol in Fig. 2). The maximal excess point ($\alpha = 192.75^\circ$, $\delta = -38.77^\circ$, marked by the $+$ symbol in Fig. 2), which is located inside this region, has the p-value $P_{\text{excess, min}} = 2.0 \times 10^{-4}$. The Centaurus A position yields the p-value $P_{\text{excess, Cen A}} =$

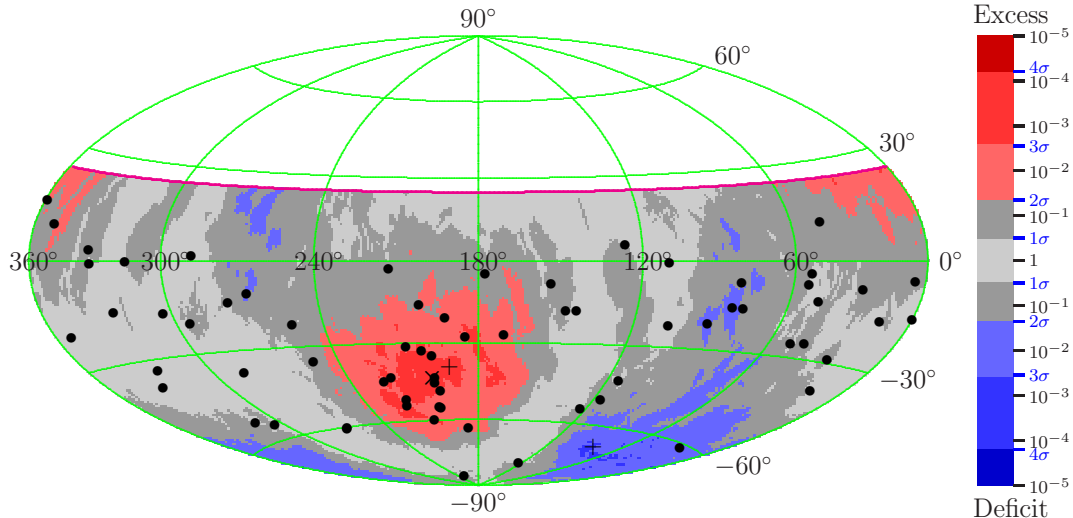


FIG. 2. The p-value map for the PAO data by the single point CADD method. The red and the blue color regions represent the excess and deficit regions whose p-value is smaller than the 2σ value ($P < 0.0455$). The + symbols mark the maximal excess and deficit points. The \times symbol marks the location of Centaurus A.

1.2×10^{-3} . The large deficit region is located near the south pole and it contains the maximal deficit point ($\alpha = 81.69^\circ$, $\delta = -67.90^\circ$, marked by the + symbol in Fig. 2), whose p-value is $P_{\text{deficit},\text{min}} = 1.2 \times 10^{-3}$. Both the excess region near Centaurus A and the deficit region near the south pole confirms that the arrival direction distribution of PAO UHECR is anisotropic.

IV. CONCLUSION

The anisotropy in the arrival directions of UHECRs observed by PAO was firstly noted in the correlation with AGNs. The observed arrival directions showed more correlation with AGNs than the isotropic distribution. It was measured by the number of correlated events, which lie within a fixed angular distance from AGNs. But since the number of AGNs is larger than the number of observed UHECRs, it is obvious that all AGNs are not the sources of UHECRs. The method adopted in this paper is quite helpful for the search of point sources of UHECR, since it scans the sky pointwisely detecting the deviation from isotropy in the arrival directions. The excess region may be an indication of UHECR source in that region. In this regard, the large excess region located near Centaurus A supports the hypothesis that Centaurus A is a promising source of UHECR [8, 14]. This fact can be used to infer the fraction of Centaurus A contribution to the whole observed UHECRs and to estimate the size of intergalactic magnetic fields in the vicinity of Centaurus A [15].

The distinguishing feature in our results of anisotropy study is the identification of a void region near the south pole. The important implication of the existence of void region in the arrival directions of observed UHECRs is that it limits the number of UHECRs contributed by the isotropic background, which is presumably considered to be the contribution from the sources outside of the GZK radius. A detailed study on this limit is in progress.

In conclusion, we adopted the point source correlational angular distance distrusting to study the anisotropy in the arrival directions of ultra-high energy cosmic rays. Our method

reveals that anisotropy in the arrival directions of UHECR observed by PAO is characterized by one prominent excess region and one void region, which confirms that the arrival direction distribution is anisotropic in the sense that it is hard to obtain from the isotropic distribution. The excess region is located near the Centaurus A direction supports that the Centaurus A is a promising UHECR source. The void region near the south pole direction may be used to limit the diffuse isotropic background contribution, that is, the contribution from outside of the GZK radius.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation (NRF) funded by the Ministry of Education, Science and Technology (2012R1A1A2008381).

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