Correlation of the UHECR with AGN using the new statistical test methods and the updated data from Pierre Auger Observatory

HANG BAE KIM AND JIHYUN KIM
Department of Physics and The Research Institute of Natural Science, Hanyang University, Seoul 133-791, Korea
hbkim@hanyang.ac.kr
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Abstract: We constructed the statistical test methods to compare the arrival direction of ultra-high energy cosmic rays (UHECR) and distributions of point sources as a candidate for the source of UHECR in our previous work. The main point of our methods is that the two-dimensional distribution of arrival directions is reduced to the one-dimensional distributions, suitable for measuring the correlation with the point sources so that the standard KS test is applied. We used the updated Pierre Auger Observatory (PAO) data as a UHECR data set and the 13th edition of Véron-Cetty and Véron (VCV) catalog as the AGN data set. Based on the AGN catalog, we have constructed Monte-Carlo simulation under two free parameters; the AGN fraction, f, and the smearing angle, θ_s. The results of our test excluded the both possibilities that the distribution of UHECR is isotropic and the observed UHECR are completely originated from the selected AGN. However, the appropriate amount of additional isotropic component either through the background contribution or through the large smearing effect makes the correlation relatively high. We hope that the data which are updated by PAO and obtained by Telescope Array experiment will give more evidence for the origin of UHECR.

Keywords: ultra-high energy cosmic rays, active galactic nuclei, angular correlation

1 Introduction

Cosmic rays (CR) have the broad energy spectrum and the sources of CR vary depending on the energies of CR. The highest part of the spectrum is most mysterious. Scientists have tried to reveal the origins of ultra-high energy cosmic rays (UHECR) for a long time. However, the sources of UHECR are still grey areas.

After the discovery of the cosmic microwave background (CMB), it was noted that there would be a suppression in the energy spectrum of UHECR above GZK energy ($E_{\rm GZK} \sim 4 \times 10^{19}\,{\rm eV}$), because of the interactions with the CMB photons [1, 2]. Fortunately, the recent observation verifies the suppression [3, 4]. This implies that main sources of UHECR with energies above GZK energy would be located within the GZK horizon (~ 100 Mpc). This helps us to search the sources within relatively close extragalactic space. Also, the trajectories of UHECR with these energies are supposed to be affected only a little by intergalactic magnetic fields. This makes it possible that statistical analyses of arrival direction of UHECR reveal the origins of them.

We have a few candidates for the sources of UHECR and the nearby active galactic nuclei (AGN) are among them. The Pierre Auger Observatory (PAO) reported that there is a correlation of arrival direction of UHECR with nearby AGN in Véron-Cetty and Véron (VCV) catalog [5]. On the contrary, the High Resolution Fly's Eye (HiRes) collaboration finds no significant correlations between the HiRes stereo data and the AGN in VCV catalog [6] and the recent analysis with updated PAO data weakens the significance of the correlation [7]. Also our previous analysis excluded a hypothesis that UHECR are completely originated from the selected AGN in VCV catalog [8]. According to our results, however, increasing isotropic components makes the AGN hypothesis for UHECR sources a viable one. In this paper, we report the updated results of our analysis using the newly released PAO data [7] and the 13th edition of VCV catalog updated in 2010 [9].

2 Simulation for the AGN hypothesis

Our simple AGN hypothesis is that the main sources of UHECR are the AGN within a certain distance. To verify this hypothesis, the updated 69 PAO data set with energies, $E \geq E_c = 5.5 \times 10^{19}\,{\rm eV}$ is used. The mock UHECR data set is obtained by our simple AGN hypothesis and the AGN as sources of UHECR used in this simulation are listed in the 13th edition of VCV catalog. We assumed that AGN within the GZK horizon ~ 100 Mpc (corresponding to the redshift $z \leq 0.024$) are the part of the sources. There are 168,941 quasars, BL Lac and AGN in the VCV catalog, which contains the information about locations, redshift and so on. The number of AGN within 100 Mpc is 865. In our simulation we used 862 AGN as source candidates except 3 AGN having zero redshift.

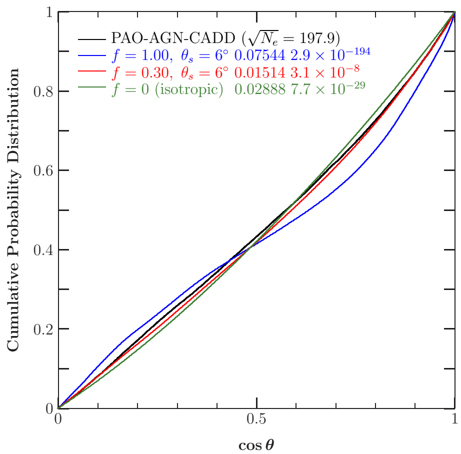

Figure 1: Cumulative probability distribution of CADD.

We considered AGN as smeared point sources of UHECR, reflecting the fact that the trajectories of UHECR can be bent by intervening magnetic fields. The smearing effect varies AGN by AGN in general. We assumed that each AGN has a Gaussian flux distribution with a certain angular width. Then the UHECR flux from all AGN is given by

$$f_{\rm AGN}(\hat{\mathbf{r}}) = \sum_{i \in {\rm AGN}} \frac{L_i}{4\pi d_i^2} \cdot \frac{1}{\pi \theta_s^2} \exp\left[-\left(\frac{\cos^{-1}(\hat{\mathbf{r}} \cdot \hat{\mathbf{r}}'_i)}{\theta_s} \right)^2 \right], \tag{1}$$

where L_i is the UHECR luminosity, d_i is the distance, and θ_s is the smearing angle of each AGN. In this work, we ignored the effects of the UHECR luminosity for simplicity and the smearing angle, θ_s, is a free parameter that we can adjust to test our hypothesis.

We have another free parameter in our simulation and that parameter is an AGN source fraction factor, f. In simple AGN model we constructed, the AGN within 100 Mpc are not the only sources of UHECR. According to the AGN fraction, f, we can mix the isotropic source and AGN source appropriately. If $f = 0$, the sources of UHECR has isotropic distribution, on the other hand, if $f = 1$, the UHECR come from AGN completely. For example, in the case of $f = 0.3$, 30% of the mock UHECR have isotropic components as their mother distribution and 70% of them have the AGN within 100 Mpc in the VCV catalog as their mother distribution.

Also we considered the geometrical limitation that UHECR experiment cannot avoid. The geometrical exposure is caused by the latitude of the experimental site on the earth and the zenith angle efficiency of detectors. Therefore the detector array cannot cover the sky uniformly [10]. The latitude of PAO site is 35.20° south and the zenith angle cut of that is 60°.

3 Statistical test methods

In order to test our simple AGN hypothesis, we need to compare the mock UHECR data obtained by our simulation with the PAO data. To prove that two distributions are different or not, we developed three test methods; correlational angular distance distribution (CADD), auto-angular distance distribution (AADD) and flux exposure value distribution (FEVD) [8]. The point of our test methods is that we reduce the two-dimensional distribution, i.e. arrival direction, to one-dimensional distribution.

CADD This is the distribution of the angular distances of all pairs UHECR arrival directions and the point source directions:

$$\text{CADD}: \left\{ \cos\theta_{ij'} \equiv \hat{\mathbf{r}}_i \cdot \hat{\mathbf{r}}'_j \mid i = 1, \ldots, N;\ j = 1, \ldots, M \right\}, \tag{2}$$

where $\hat{\mathbf{r}}_i$ are the UHECR arrival directions, $\hat{\mathbf{r}}'_j$ are the point source directions, and N and M are their total numbers, respectively. This is an improvement of previously adopted methods [5, 11, 12] and most useful when we consider the set of point sources for UHECR.

AADD This is the distribution of the angular distances of all pairs of UHECR arrival directions:

$$\text{AADD}: \left\{ \cos\theta_{ij} \equiv \hat{\mathbf{r}}_i \cdot \hat{\mathbf{r}}_j \mid i, j = 1, \ldots, N \right\}, \tag{3}$$

where $\hat{\mathbf{r}}_i$ are the UHECR arrival directions and N is the total numbers of UHECR. The AADD method may not be directly relevant for examining the correlation between the UHECR arrival directions and the point sources because it just measures the self-correlation of UHECR. It was used previously to examine the clustering of CR arrival directions [13, 14, 15, 16].

FEVD At a given arrival direction, the expected flux value is the product of the UHECR flux expected from the UHECR source model and the exposure function of the detector at that direction. FEVD is the distribution of expected flux values at UHECR arrival directions:

$$\text{FEVD}: \left\{ F_i \equiv f(\hat{\mathbf{r}}_i) h(\hat{\mathbf{r}}_i) \mid i = 1, \ldots, N \right\}, \tag{4}$$

where $\hat{\mathbf{r}}_i$ are the UHECR arrival directions, N is the total numbers of UHECR, $f(\hat{\mathbf{r}}_i)$ and $h(\hat{\mathbf{r}}_i)$ are the UHECR flux and the exposure function, respectively. It was proposed by Koers and Tinyakov [17] to test the correlation between the galaxy distribution and the UHECR.

One of the advantages of our test methods is that we can avoid the arbitrary binning which the previous researches have adopted by sweeping the angular distance from 0° to 180° when we calculate the CADD and AADD. And we can apply these quantities to the standard Kolmogorov-Smirnov (KS) test to test our hypotheses because CADD, AADD and FEVD are 1-dimensional.

We can get the KS statistic directly from the cumulative probability distribution of the mock UHECR and PAO UHECR. That is the KS statistic D is the greatest distance between the two cumulative distributions and given by [18]

$$D = \max \left| S_{N_1}(x) - S_{N_2}(x) \right|, \tag{5}$$

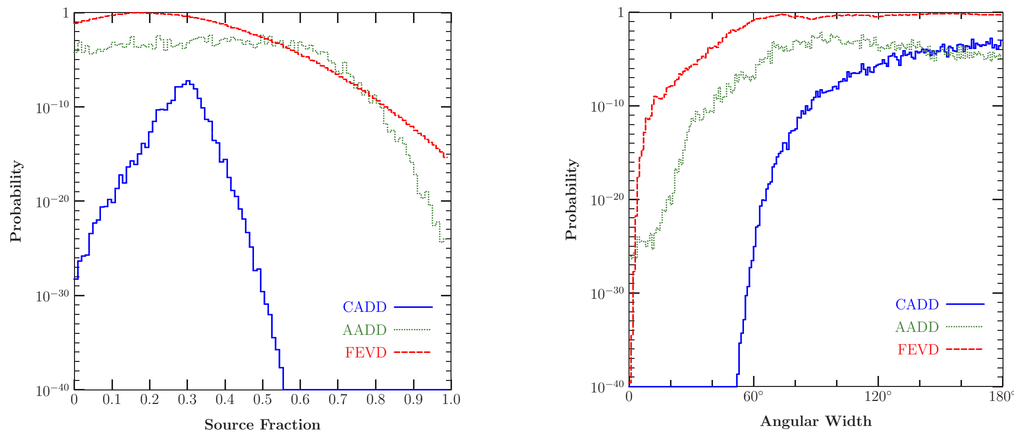

Figure 2: Dependencies on source fraction, f, and smearing angle, θ_s.

where $S_{N_1}(x)$ and $S_{N_2}(x)$ two different are cumulative distribution functions.

The probability that the two distributions come from same one is given by

$$\text{Probability} = Q_{\text{KS}}\left(\left[\sqrt{N_e} + 0.12 + 0.11/\sqrt{N_e}\right] D\right), \quad (6)$$

where $Q_{\text{KS}}(\lambda) = 2\sum_{j=1}^{\infty}(-1)^{j-1}e^{-2j^2\lambda^2}$ and N_e is the effective number of data points, $N_e = N_1N_2/(N_1 + N_2)$. When the number of observed UHECR events is N_o and the number of AGN is M, $N_1 = N_oM$ for CADD, $N_1 = N_o(N_o - 1)/2$ for AADD, and $N_1 = N_o$ for FEVD. For N_2, we replace N_o with N_s, the number of simulated UHECR events. In this work, the number of AGN is 862 and the number of mock UHECR is 10^5.

4 Results

The cumulative probability distributions of example of our test results are given in Fig. 1. This is the base to calculate the KS probability as mentioned above. The small KS statistic, D, means the two distributions have high probability that they come from the same population. The black line is for the PAO data, blue line is for the case of $f = 1$ and $\theta_s = 6°$ and green line is for that of isotropic. The red line is the simulation result which is the best to explain the PAO data among these. We iterated this process and found the dependencies on each parameter, f and θ_s.

The details are given in Fig.2. The blue line is the result of CADD, the green line is that of AADD and the red line is that of FEVD. The results of CADD are crucial to compare the distribution of AGN and UHECR.

The left figure of Fig.2 shows the dependency on the AGN fraction, f. (We set $\theta_s = 6°$.) The probabilities of each limit, $f = 1$ (all UHECR from selected AGN) and $f = 0$ (complete isotropy) is extremely small. This means the hypothesis that UHECR with energies higher than 5.5×10^{19} eV come from AGN within 100 Mpc in VCV catalog can be excluded. And it can be said that the distribution of UHECR is anisotropic also. The interesting thing is that CADD has the peak probability, $P = 6.07 \times 10^{-8}$ at $f = 0.3$, even if the absolute value is quite small. We cannot explain the experimental data using both limits of $f = 0$ and $f = 1$, however, it could be possible to explain the distribution of UHECR by the proper mix of sources. The tendency is consistent with our previous work [8], although the exact peak f value is slightly different.

We can see the dependency on smearing angle, θ_s in right panel of Fig.2. (We set $f = 1$.) The large θ_s means that the trajectory of UHECR is bent a lot from the original direction toward the earth. According to our results, the larger smearing angle has a good probability to explain the PAO data. This result is slightly different from the previous results [8]. The updated data need more isotropic components of source obtained by AGN fraction/smearing angle.

Here is the one more interesting result. We tested the possibility that a certain class of AGN are the only the sources of UHECR. As the first stage, we checked the AGN lie within a certain region are actually responsible for the UHECR. The left panel of Fig.3 shows the probabilities. The mock data generated by the AGN lie between 60 to 80 Mpc have relatively high probability, $P = 1.89 \times 10^{-3}$. The skymap of PAO data (red circles) and AGN with distance $60 < d \leq 80$ Mpc (blue asterisks) is given in right panel of Fig.3. We don't have appropriate physical explanation yet, however, it looks very interesting, because of the similar results from Ryu *et al.* [19].

5 Conclusion

We tested the AGN hypothesis for UHECR sources using the test methods we developed, in which the two-dimensional arrival direction distribution is reduced to the one-dimensional probability distribution, CADD, AADD and FEVD, and the standard KS test is applied.

Our simple AGN hypothesis is that AGN within 100 Mpc are the main source of UHECR. Additionally we introduced the isotropic component to improve the test results.

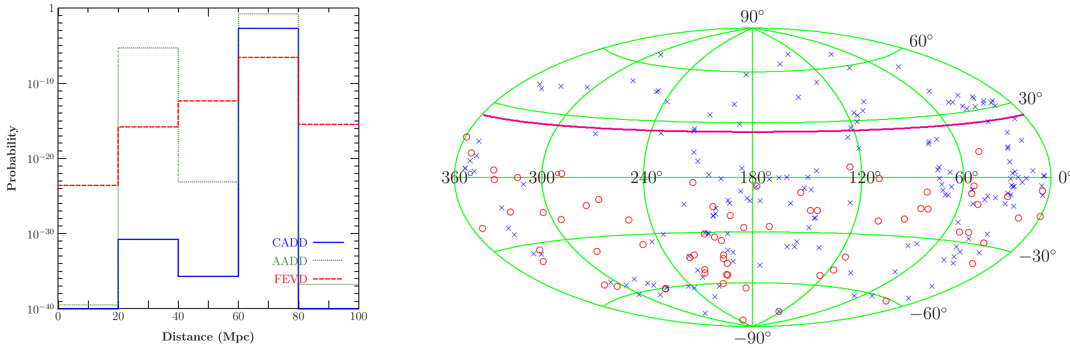

Figure 3: Dependency on distance and the skymap of Hammer projection in equatorial coordinate of PAO data and AGN between 60 o 80 Mpc.

The AGN was taken from the 13th edition of VCV catalog and the updated PAO data was used.

In conclusion, we could reject the hypothesis that the whole UHECR come from AGN within 100 Mpc. It was also ruled out that the distribution of UHECR is isotropic. However, if we consider the mixture of AGN and isotropically distributed sources as the sources of UHECR or the effect of large deflection angle, AGN can still be possible sources of UHECR.

For further research about the sources of UHECR, the arrival direction analysis is essential. In that sense, the data that will be obtained both by Telescope Array (TA) experiment and by PAO is very crucial because they cover the whole sky when combined.

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