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A Bayesian analysis of correlation between AGNs and ultra high energy cosmic rays detected by the Telescope Array Experiment

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Ultra high energy cosmic rays over $10^{19}eV$ are thought to come from very powerful objects such as Active Galatic Nucleus(AGN). However, the number of AGNs and ultra high energy cosmic rays is not large enough to experimentally declare the correlation between them. We use Watson and Mortlock's bayesian statistical method to compare the arrival direction data of large ground arrays such as the Telescope Array experiment with AGNs in the Veron-Cety and Veron (VCV) catalog. We also test the linearity using toy monte carlo simulation. In this presentation, we present the probability that the TA's cosmic rays come from AGNs.

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1. Introduction

'What is the source of ultra high energy cosmic ray(UHECR)?' is one of the key questions in cosmic ray research. Large-scale ground array experiments such as Telescope Array(TA) in the northern hemisphere and Pierre Auger Observatory(PAO) in the southern hemisphere are detecting UHECRs and are studying origins of them. Many studies have discussed active galactic nuclei(AGN) as a potential candidate for a powerful UHECR source. Watson's study of the correlation between PAO's experimental results and the AGN by bayesian analysis is similar to other studies[1]. The ground detector array measures cosmic rays indirectly through air showers. A investigation of the air shower signal can be used to estimate the incident direction of the primary particles, where the directional error has a high accuracy within a few degrees. The AGN data were obtained from the Veron-Cetty and Veron (VCV) catalogue[3]. The first step of the study assumes that there was no directional distortion while cosmic rays launched from AGN reached Earth. With these assumptions, Watson's paper concluded that PAO's UHECRs are almost isotropic, regardless of AGN. Here we will compare the results of the TA's cosmic rays to VCV's AGN in a same way and look at results.

2. Method

The Bayesian method is as follows. All eqations in this section are from Watson *et al.*

Divide the celestial into 180 sections in the DEC. direction and 360 sections in the R.A. direction[1]. In this case, the emission rate from the source and the emission rate from the background are defined as Γ_{src} and R_{bkg}[1]. Since the prior probabilty is approximated by a step function, the posterior probability distribution can be considered to be proportional to the Likelihood function[1].

$$Pr(\Gamma_{src},R_{bkg}|data) = \frac{Pr(\Gamma_{src},R_{bkg})Pr(data|\Gamma_{src},R_{bkg})}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Pr(\Gamma_{src},R_{bkg})Pr(data|\Gamma_{src},R_{bkg})d\Gamma_{src}dR_{bkg}} \tag{2.1}$$

$$Pr(\Gamma_{src},R_{bkg}|data) \propto \Theta(\Gamma_{src})\Theta(R_{bkg})Pr(data|\Gamma_{src},R_{bkg}) \tag{2.2}$$

2.1 The full likelihood function in Watson *et al.*

The full likelihood function is as follows.

$$Pr(N_{c,p}|\Gamma_{src},R_{bkg}) = \prod_{p=1}^{N_p} \frac{(\overline{N}_{c,p})^{N_{c,p}}\exp(-\overline{N}_{c,p})}{N_{c,p}!} \tag{2.3}$$

$N_{c,p}$is the number of cosmic ray events counted for each pixel[1]. Assume that the probability distribution follows a Poisson distribution[1].

$$\overline{N}_{c,p} = \int_p \varepsilon(\hat{r}_{obs})d\Omega_{obs} \times [R_{bkg} + \sum_{s=1}^{N_s} Pr(\hat{r}_{obs}|\hat{r}_s)\frac{dN_{arr}(E_{obs} \geq E_{min}, D_s)}{dtdA}] \tag{2.4}$$

Consider the observation area of each pixel and the smearing angle of the incident direction in the above equation. $d\varepsilon/d\Omega$ is the exposure per unit solid angle[1]. $Pr(\hat{r_{obs}}|\hat{r}_s)$ is a gaussian distribution caused by the smearing angle effect[1]. D_s is distance to each source[1].

$$\frac{dN_{emit}(\geq E)}{dt} = \Gamma_{src}(\frac{E}{E_{min}})^{-\gamma} \tag{2.5}$$

Consider the energy spectrum of the flux reduction γ of 3.6 with increasing energy with a minimum value E_{min} of 5.7×10^{19} eV for UHECRs[3].

$$E_{arr} = \max[E_{GZK}, E_{emit}(1 - f_{GZK})^{D_s/L_{GZK}}] \tag{2.6}$$

$$\frac{dN_{arr}(E_{obs} \geq E_{min}, D_s)}{dtdA} = \Gamma_{src}\frac{(1 - f_{GZK})^{\gamma D_s/L_{GZK}}}{4\pi D_s^2} \tag{2.7}$$

The GZK effect is considered as in the above equation. $f_{GZK} = 0.2$ is the average fractional energy loss per GZK interaction and $L_{GZK} = 4Mpc$ is the GZK mean free path[1].

The number of cosmic ray from the background can be thought of as:

$$\overline{N}_{bkg,p} = R_{bkg}\int_p \frac{d\varepsilon}{d\Omega} d\Omega_{obs} \tag{2.8}$$

The number of cosmic ray from the source and the number of cosmic ray from the background can be summarized as below equations[1].

$$\overline{N}_{src,p} = \sum_{s=1}^{N_s} \frac{dN_{arr}(E_{obs} \geq E_{min}, D_s)}{dtdA}\int_p \frac{d\varepsilon}{d\Omega} Pr(\hat{r}_{obs}|\hat{r}_s) d\Omega_{obs} \tag{2.9}$$

$$\overline{N}_{src,p} = \sum_{s=1}^{N_s} \Gamma_{src}\frac{(1 - f_{GZK})^{\gamma D_s/L_{GZK}}}{4\pi D_s^2}\int_p \frac{d\varepsilon}{d\Omega} Pr(\hat{r}_{obs}|\hat{r}_s) d\Omega_{obs} \tag{2.10}$$

$dE/d\Omega$(which has units of area $\times$ time) is a function of declination only[2].

The AGN data were obtained from the VCV catalog 13th ed.[3].

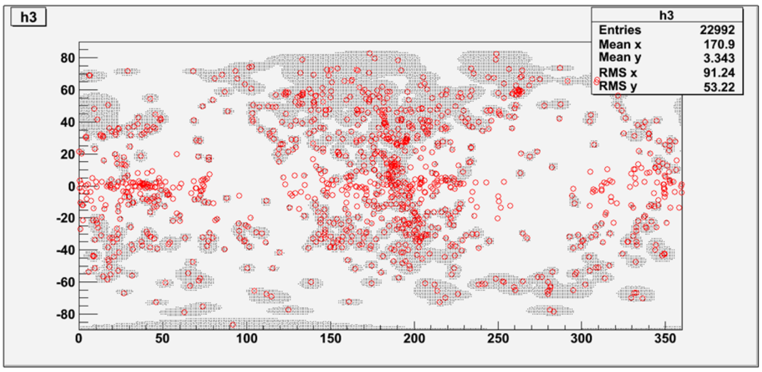

Figure 1: AGN and PAO's UHECRs coordinates in Celestial. red circles are AGNs and grey shadows are coordinates that cosmic rays can be observed when smearing angle is considered.

The TA UHECR list was from T. Abu-Zayyad *et al.*[4].

We also performed linearity test according to source ratio(Γ_{src}) through Monte Carlo simulation.

3. Result

3.1 The simple likelihood fuction test

A simple version was performed to verify that the indicator, F_{AGN} was calculated for the ratio of the source,Γ_{src}. The simple likelihood function is as follows.

$$\overline{N}_{c,p} = R_{bkg} + \sum_{s=1}^{N_s} \Gamma_{src} \tag{3.1}$$

$$Pr(N_{c,p}|\Gamma_{src}, R_{bkg}) = \prod_{p=1}^{N_s} (\overline{N}_{c,p})^{N_{c,p}} \exp(-\overline{N}_{c,p}) \tag{3.2}$$

$$= A \times {N_{src}}^{N_{src}} \exp(-N_{src}) \times {N_{bkg}}^{(27-N_{src})} \exp(-N_{bkg}) \tag{3.3}$$

To modify simply, the effect of energy, pixel area, arrival angle error are removed. Γ from source or R from background fills one pixel completely. And UHECR emission rate per each pixel was assumed a constant. In the Figure 2, the left figure shows $F_{AGN} = 1$ case and the middle figure is $F_{AGN} = 0$ case. The right figure shows case that $F_{AGN} = 0.14$ is assumed 4 of 27events. A simple version shows that the ratio value is calculated correctly.

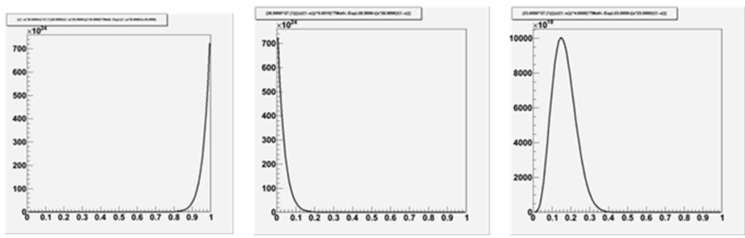

Figure 2: The probability distributions of simple likelihood functions. Left figure shows case that all cosmic rays are from AGN. And figure on center shows case that all cosmic rays are from background. On the right figure, $F_{AGN} = 0.14$ is assumed that only 4 cosmic rays of 27 events came from source.

The probability distributions by the full likelihood function are obtained as Figure 3,4 and 5.

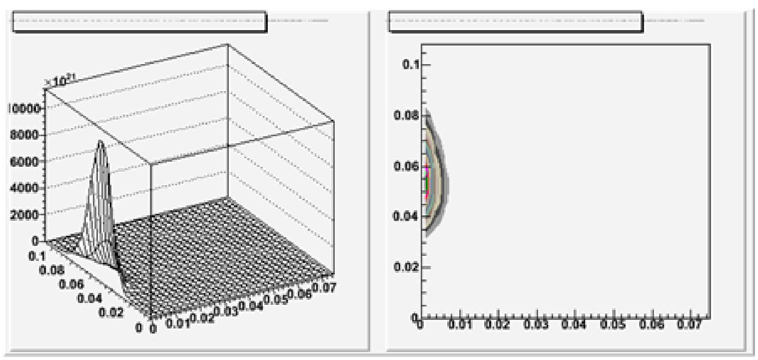

Figure 3: The probability distributions using full likelihood function. $F_{AGN} = 1$ case.

The results of the linearity test are Figure 6.

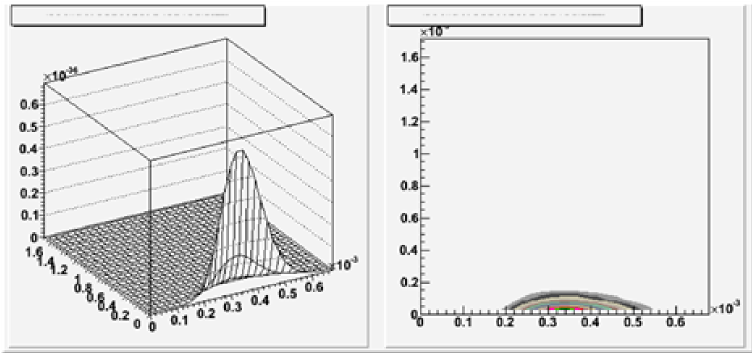

Figure 4: The probability distributions using full likelihood function. $F_{AGN} = 0$ case.

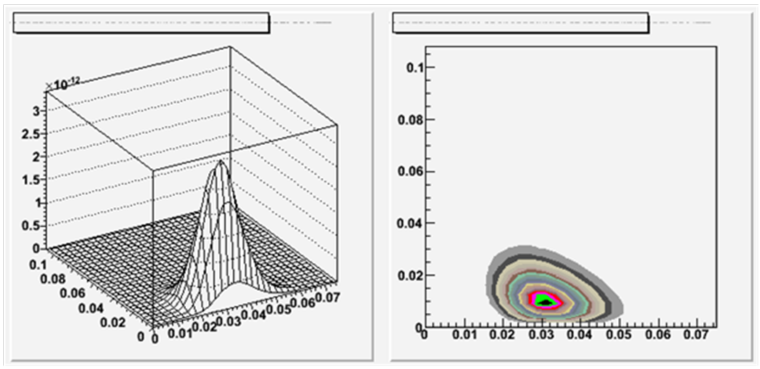

Figure 5: The probability distributions using full likelihood function. TA's UHECR case.

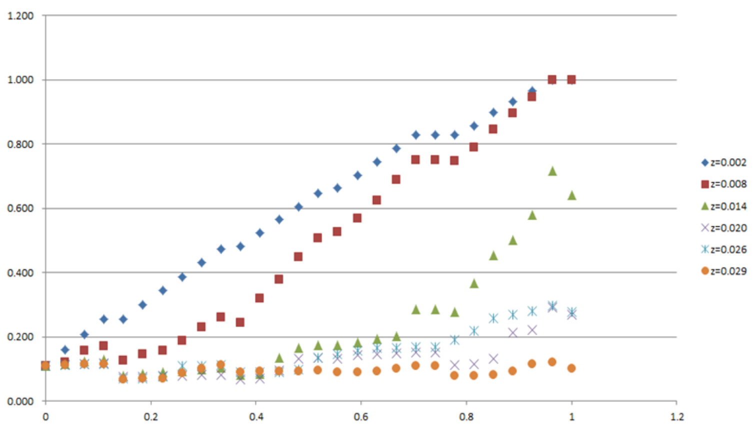

Figure 6: The result of linearity test

dec.	smearing angle	F_{AGN}
$-95 \sim 25$	6	18.92
$-95 \sim 25$	10	27.45

Table 1: F_{AGN} of TA's UHECR by smearing angle

4. Discussion

Figure 3 ∼ 5 and Table 1 are bayesian analysis results of TA's UHECR and AGN from VCV. Y axis in the figure is R_{bkg} and X axis is Γ_{src}. Considering a smearing angle as 6 degree, F_{AGN} is 18.92. In Figure 6, Y axis is the calculated F_{AGN} and X axis is the virtually setting F_{AGN}. According to variables like smearing angle which are shown as colored dots, growth rates are different. However, Y intercept is almost the same, and it can be confirmed that it is not zero. Therefore, results should to be calibrated to smaller values through linearity tests that were not performed in previous studies. According to this test, results give an interpretation that is much more isotropic than the calculated value. We will be able to develop bayesian searches for objects other than AGN to better understand the relationship between objects and cosmic rays.

5. Summary

One of the key questions in cosmic rays research is the question of the origin of UHECRs. There is a study that have found the relationship between PAO's UHECRs and AGN using the bayesian analysis among the many studies to find cosmic ray source and anisotropy. The study of this proceeding was conducted to get a hint from the Watson's paper and to investigate the relationship between TA experiment and AGN.

The AGN coordinates was from VCV catalog. 22 UHECRs were used for this analysis. The probability distribution was calculated as follows. As a result of the linearity test, we found that the probability has to be corrected. We will proceed with further research to advance the Bayesian equation in the future and search using galaxy distribution or mass distribution instead of AGN.

References

[1] Laura J. Watson *et al.*, *A Bayesian analysis of the 27 highest energy cosmic rays detected by the Pierre Auger Observatory*, *Mon. Not. R. Astron. Soc.* **418**, 206 (2011) [https://doi.org/10.1111/j.1365-2966.2011.19476.x].

[2] Z. Fodor and S. D. Katz, *Ultrahigh energy cosmic rays from compact sources*, *Phys. Rev. D* **63**, 023002 (2000) [https://doi.org/10.1103/PhysRevD.63.023002].

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