

Constraining UHECR flux from AGN with the data of the Yakutsk array

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Abstract. Recent claims of the significant correlation between active galactic nuclei (AGN) and arrival directions of ultra-high energy cosmic rays (UHECRs) have intensified efforts towards the CR origin. In this paper, the Yakutsk array data are re-analyzed to check whether there is an appreciable flux of particles from these objects different from the bulk of CRs. Namely, a difference in ages of air showers induced by UHECRs from AGN vicinity and those from all other directions is searched for. The aim is to set a limit to the flux of particles from AGN other than protons.

Keywords: Extensive air shower (EAS)

I. INTRODUCTION

A direct way to find the hypothetical sources of ultra-high energy cosmic rays (UHECRs) is the search for correlation of CR arrival directions with the celestial objects surmised. A good deal of effort has been undertaken in this way.

In particular, NRI group from Moscow applied in the series of papers [1] the selection criteria to assemble catalogs which show a maximum correlation with arrival directions of UHECRs above a threshold energy. As a result, UHECRs observed in AGASA, HiRes and Yakutsk experiments were found to have significant correlations with a subset of the most powerful confirmed BL Lacs at energies $E_0 > 40$ EeV ($= 4 \times 10^{18}$ eV). After assigning penalties for subset selection and bin adjustment, the probability of such a correlation to occur by chance in a random distribution was ascertained as 10^{-4} .

The Pierre Auger Observatory (PAO) collaboration [2] analyzed a sample consisting of 81 EASs with energies above 40 EeV detected from January 1, 2004 to August 31, 2007. The authors used a part of the data (to May 27, 2006) in order to determine the parameters resulting in the maximum correlation of UHECR arrival directions with AGN. Then, the second part of the data was used to confirm the hypothesis obtained.

The observed UHECR arrival directions are found to be anisotropic, and there is a significant correlation of EASs with energies above 56 EeV within an angle of $\psi = 3.1^\circ$ with AGN from catalog [3] located at distances $z \leq 0.018$ from the Earth. In the second part of the data (from May 27, 2006), 8 of 13 EASs correlate with AGN under the same conditions that have been found for the first part of the data, while the number of expected coincidences is 2.7 in the isotropic case. This

corresponds to the chance probability $P = 1.7 \times 10^{-3}$ for the uniform distribution.

This result is confirmed by the Yakutsk array data [4], while the HiRes data demonstrate no significant correlation with AGN [5].

NRI group stated contrary to the PAO hypothesis [6]: the conclusion that the bulk of UHECRs are protons originating in nearby AGN can be rejected at 99% CL. Instead, they attribute PAO observational data to the existence of a bright source in the direction of the Centaurus A. Another interpretation of the data was proposed by Wibig and Wolfendale [7], namely, that cosmic rays are nuclei with $\overline{\ln A} = 2.2 \pm 0.8$ generated in radio galaxies.

In this paper another approach is used to distinguish possible CR flux from the source candidate objects basing on extensive air shower age variance due to the different primary particles. Here, 'age' means a stage of the cascade development at the observer's level, $s = 3X_L/(X_L + 2X_{max})$, where X_L, X_{max} are the observer and the shower maximum depths in the atmosphere.

The method is convenient to reveal the difference in EAS development rather than to search for excess flux from the possible sources of UHECRs. An advantage of the method is that it belongs to some few one able to indicate different primary particles. The Yakutsk array data are analyzed in the energy range above 1 EeV searching for a difference in the shower age between samples.

II. SLOPE OF THE LATERAL DISTRIBUTION FUNCTION VS THE SHOWER AGE

In accompanying paper in Proceedings of this conference [8] it is shown that a slope of lateral distribution function (LDF) of charged particles on the ground¹ can be used as an indicator of EAS age. The Monte Carlo modeling of showers with CORSIKA code is used to demonstrate that the dependence of LDF shape on the primary energy, mass composition and shower angles are parameterized by s , in a good approximation. Of course, it concerns the average values only; fluctuations disperse the relation according to the sample size.

In the present work the LDF slope of charged particles detected with scintillators of the Yakutsk array is used to distinguish young and old showers in the given energy and zenith angle intervals. The dataset used consists of events collected during a period 1974 to 2004, with a

¹as well as the mean radius of LDF

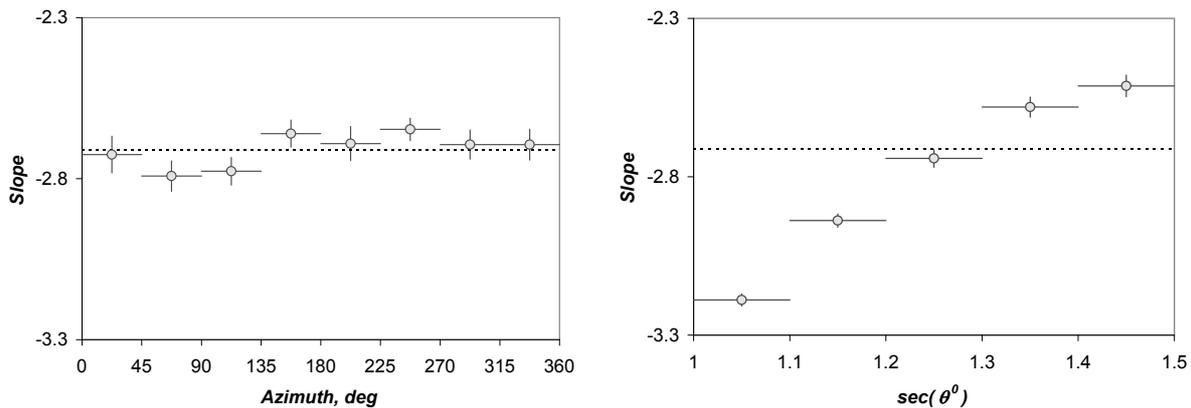


Fig. 1: Average slope of lateral distribution function of charged particles as a function of azimuth and zenith angle. Showers are detected with the Yakutsk array. $E_0 = 4.5 \pm 0.5$ EeV.

total of 19407 showers selected with energies from 1 to 100 EeV, zenith angles $\theta < 50^\circ$ and axes within array area. In order to estimate LDF slope, η , of each shower in a set, additional selection criteria were applied: i) at least 4 stations at the core distance $r \in (200, 1000)$ m should have particle density above threshold; ii) the slope calculated using least square method should be in the interval $\eta \in (-5, 0)$.

According to Linsley's Elongation Rate theorem [9], X_{max} is a function of the primary energy and mass but is independent of zenith and azimuth angles. This is intrinsic feature of the electromagnetic sub-cascades, that is manifested in the radiation length and critical energy independent of the shower angles. An immediate consequence is that the showers of the same energy but different zenith angles have the same maximum slant depth in g/cm^2 .

Selecting EAS events in the narrow energy bin² with various arrival directions we demonstrate the age dependence of the LDF slope in measured showers (Fig. 1). We have selected EASs with energy $4 < E_0 < 5$ EeV; showers are grouped in 45° azimuth bins and $\sec \theta$ bins of 0.1 widths. The average slope in a sample is shown by the horizontal line. Due to the shower age independent of azimuth, ϕ , LDF slopes concentrate around the average (left panel); $\partial \eta / \partial \phi = 0$ within experimental errors. On the contrary, due to $X_L = X_0 \sec \theta$, where $X_0 = 1020$ g/cm^2 in Yakutsk, the LDF slope is a monotonous function of the shower age (right panel).

A derivative of LDF slope with respect to $\cos \theta$ transforms³ to that with respect to the age:

$$\frac{\partial \eta}{\partial \cos \theta} = -\frac{2}{3} s^2 \frac{d\eta}{ds} \frac{X_{max}}{X_0}.$$

III. WILCOXON RANK SUM CRITERION

A non-parametric alternative to the paired t-test, namely Wilcoxon rank sum criterion [10], is used in this

work which is similar to the Fisher test. A difference is that this test assumes: there is no information about the form of the initial distribution⁴. As long as we are not sure the distribution of LDF slope is Gaussian, we have to use a non-parametric method which is applicable to any distribution. Wilcoxon test is useful for deciding whether or not the two independent samples of observations belong to the same original distribution. The null hypothesis is that the two samples are drawn from a single population.

In order to apply a Wilcoxon test to the samples of air showers correlated/uncorrelated in arrival directions with AGN and other objects of interest, we have used the rank sum of LDF slopes in two series of events. An idea is that these series can differ in primary particles EAS originate from (e.g., Wibig & Wolfendale hypothesis mentioned above [7]). Different primary particles result in different ages of the showers (with the same energy and zenith angle) and consequently, different slopes of charged particles' LDF on the ground which can be revealed by the surface array.

The resolving power of Wilcoxon test was demonstrated in the previous paper [11] as a function of the LDF slope difference and the sample size, applying the procedure to a pair of samples of EAS events selected in the narrow θ, E_0 intervals. A rank sum of LDF slopes was then used to distinguish samples at the 99% confidence level.

Here, the application of the method will be illustrated in examples only, to diversify the description. If one selects two samples of EAS (induced by the same primary particles) of the same energy at the different zenith angles, then these samples have the same X_{max} but different ages. As was shown above, LDF slopes are different, too. Applying Wilcoxon test, one can distinguish these samples if the number of showers is sufficient.

²we suppose here the same primary particles

³ X_{max} is const

⁴t-test, as well as Fisher's, is applicable in the case of the normal distribution only

Example 1. Two samples of events detected with the Yakutsk array. The energies are within (7, 8) EeV interval; i) sample A: 26 events with $1 < \sec \theta < 1.1$; ii) sample B: 13 events at $1.3 < \sec \theta < 1.4$. The rank sum of observed LDF slopes is 399, while 520 is expected if two samples are drawn from the same population, r.m.s. deviation of the rank is 33.6. The null hypothesis can be rejected at the 99.98% confidence level.

Example 2. The same energy interval; i) sample A: 23 events with $1.1 < \sec \theta < 1.2$; ii) sample B: 13 events at $1.3 < \sec \theta < 1.4$. The rank sum of observed LDF slopes is 378, while 425.5 is expected, r.m.s. is 30.36. The null hypothesis can not be rejected. The difference in average slopes is 0.2 in this case; the number of events is insufficient to distinguish samples.

IV. EAS EVENTS FROM AGN VS BACKGROUND: IS THERE ANY AGE DIFFERENCE?

We need two samples of data in order to compare LDF slopes of showers. The first one is composed of UHECRs pointing back via arrival direction to the AGN vicinity. In this case, the angular distance is calculated between each EAS arrival direction and the position of AGN, selected from the catalog. Those showers having the distance less than 3° are marked 'On', and are accumulated in the subset *A*. The bin size $\psi = 3^\circ$ has been shown to provide a minimum of the chance probability of angular correlation between AGN and UHECRs observed to be occurred in the isotropic distribution, using the dataset of the Yakutsk array [4]. At the same time, it is close to the angular uncertainty in arrival direction of EAS events detected with this array.

Another sample of data in the same energy/zenith angle bins is composed as follows. For each EAS event in the ψ vicinity of AGN a counterpart event is found closest in zenith angle and energy which is not marked 'On'. Marking it 'Off' (subset *B*), we get two equal subsets of EAS data - correlated in arrival directions with AGN and the background data - congruous to the circumstances of zenith angle and energy.

Having two subsets⁵ of EAS events we can apply Wilcoxon rank sum test in order to decide: is there any appreciable difference in LDF slope of the showers in subsets *A/B* or these samples are drawn from the same distribution? To do so, we have to count up the rank sum, W , of subsets *A* or *B* combined into one set. Here, the rank is a serial number of the element in ascending sequence. Consulting with statistical tables about the deviation of the statistic W from the expected value $N(2N + 1)/2$, we can accept or reject the null hypothesis at the significance level specified.

If there is a significant difference in LDF slope (age) of the showers in samples *A* and *B*, then we can conclude that EAS primary particles in these samples are different.

⁵sizes are N

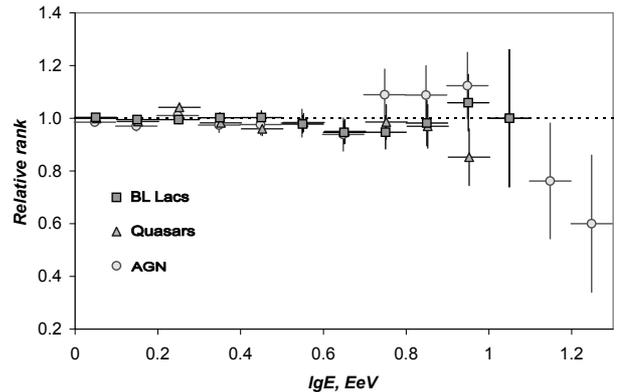


Fig. 2: The rank sum for pairs of 'On/Off' samples in the case of three classes of extragalactic objects. Vertical bars are RMS deviations of the sum in ratio to the expected rank sum; horizontal bars are energy bin widths.

Three classes of objects from 12th edition of the Veron's catalog are assumed as possible sources of UHECRs in this paper:

- i) AGN at the distances $z < 0.015$;
- ii) quasars at $z < 0.3$;

iii) BL Lacs with optical magnitude $m < 18$ classified as 'BL'. The results of *A* and *B* samples comparison are given in Fig. 2. A ratio of observed rank sum to that expected in the null hypothesis case is shown for three classes of candidate objects.

There is no appreciable difference in LDF slopes in all three cases. Basing on the shower simulation using CORSIKA code we can constrain particular types of EAS primary particles which are hypothesized to originate in AGN/Quasars/BL Lacs. The main assumption here is that the background EAS events in the sample *B* are induced by extragalactic protons.

In the first line of Table I are given the LDF slope differences in EAS, $d\eta$, induced by iron nucleus and photons in comparison with proton-initiated showers calculated in two models. A minimal sample size, N_{min} , needed to distinguish a given slope difference using the Wilcoxon test, is given in the second line for models/primaries. Corresponding threshold energies, E_{thr} , are shown for candidate sources and primary particles in the last three lines of Table.

V. CONCLUSIONS

The Yakutsk array data are analyzed in order to reveal a possible difference in the age of air showers corre-

TABLE I: The limits of the primary Fe and γ energies

	EPOS, Fe	QGSJETII, Fe	QGSJETII, γ
$d\eta$	0.23 ± 0.01	0.245 ± 0.015	0.355 ± 0.025
N_{min}	70 ± 15	53 ± 15	18 ± 1
E_{thr}^{AGN} , EeV	3	4	5
E_{thr}^{Quas} , EeV	4	5	8
E_{thr}^{BL} , EeV	4	5	10

lated/uncorrelated with AGN, Quasars and BL Lacs due to different primary particles. Two independent samples of UHECRs are compared using Wilcoxon rank sum criterion. The results are summarized as follows.

No difference is found in the LDF slope parameter of the two subsets of EAS events with energies above 1 EeV correlated/uncorrelated with AGN, Quasars and BL Lacs from 12th edition of Veron's catalog. The lower limit is set to the energies of iron nuclei and photons originating in these objects, assuming that the background EAS events are extragalactic protons. Due to the scarcity of EAS events detected with the Yakutsk array above $E_0 = 1$ EeV, these limit energies are below reasonable values for the extragalactic sources.

A more promising approach may be the analysis of PAO and/or HiRes data, via sampling X_{max} of showers. In this case, an advantage is that the maximum slant depth is independent of zenith angle. So the samples A and B can be selected with equal energies, ignoring θ . This will result in increased size of congruent samples selected with arrival directions 'On' and 'Off' the AGN. Together with giant acceptance area of the PAO it can lead to the resolving power sufficient to distinguish primary nuclei above 10 EeV.

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