

BL Lacertae are probable sources of the observed ultra-high energy cosmic rays

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We calculate angular correlation function between ultra-high energy cosmic rays (UHECR) observed by Yakutsk and AGASA experiments, and most powerful BL Lacertae objects. We find significant correlations which correspond to the probability of statistical fluctuation less than 10^{-4} , including penatly for selecting the subset of brightest BL Lacs. We conclude that some of BL Lacs are sources of the observed UHECR and present a list of most probable candidates.

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Introduction. Identification of sources of ultra-high energy cosmic rays (UHECR) is extremely important. Knowing production sites of UHECR will help to explain the apparent absence of the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1] by selecting a particular class of models. In the case of astrophysical origin it will give an invaluable information on physical conditions and mechanisms which may lead to acceleration of particles to energies of order 10^{20} eV. In the case of extragalactic origin, it will provide a direct information about poorly known parameters which influence propagation of UHECR, such as extragalactic magnetic fields and universal radio background.

There are observational reasons to believe that UHECR are produced by compact sources. It has been known for quite a while that the observed highest energy cosmic rays contain doublets and triplets of events coming from close directions [2–4]. Our recent analysis [5] based on the calculation of angular correlation function shows that explanation of clusters by chance coincidence is highly improbable: the correlation function for Yakutsk events [6] with energies $E > 2.4 \cdot 10^{19}$ eV has an excess at 4° which would occur with probability $2 \cdot 10^{-3}$ for the uniform distribution, while the correlation function for AGASA events [3, 7] with energies $E > 4.8 \cdot 10^{19}$ eV has an excess at 2.5° corresponding to chance probability $3 \cdot 10^{-4}$. The combined probability of the fluctuation in both sets is 4×10^{-6} . So significant autocorrelations should imply also large correlation of these events with their actual sources. It is a purpose of the present paper to identify these sources.

The clustering of UHECR by itself imposes certain constraints on possible source candidates. With the observed fraction of events in clusters, the total number of sources can be estimated along the lines of Ref. [8] to be of order several hundred. If the GZK cutoff is absent (or at energies below the cutoff), this estimate gives the number of sources in the entire Universe. Thus, to produce observed clustering, the extragalactic sources have to be extremely rare as compared to ordinary galaxies. Taking 10^3 uniformly distributed sources for an estimate, the closest one is at the redshift $z \sim 0.1$.

Various astrophysical candidates such as neutron stars, supernovae, gamma-ray bursts, colliding galaxies, active galactic nuclei (AGN), lobes of radio-galaxies, dead quasars and others (for a review see Refs.[9] and references therein) have been proposed as sources of UHECR. Possible connection of highest-energy cosmic rays with these objects was considered in Refs. [3, 4, 10]. In this paper we study correlations of UHECR with BL Lacertae (BL Lac) objects which comprise a subclass of AGN. Our motivations for selecting BL Lacs are as follows. If AGNs are sources, only those which have jets directed along the line of sight, or blazars, can correlate with observed UHECR events (regardless of the distance to a blazar in a world without GZK cut-off), since particles accelerated in a relativistic jet are strongly beamed. Blazars include BL Lacs and violently variable quasars with flat and highly polarized spectra. These spectral features give direct indication of seeing a relativistically beamed jet very close to the line of sight. BL Lacs is a subclass of blazars characterized, in addition to the above spectral features which they share, by the (near)

absence of emission lines in the spectra. This very important distinction indicates low density of ambient matter and radiation and, therefore, more favorable conditions for acceleration to highest energies.

The most recent catalog of AGNs and quasars contains 306 confirmed BL Lacs [11]. While this is the richest catalog we are aware of, it still may be incomplete. However, this is not crucial for establishing correlations between BL Lacs and UHECR events. Correlations of BL Lacs with UHECR were not studied before. We show that these correlations do exist and are statistically significant.

Method and results. Our method is based on calculation of the angular correlation function and is similar to the one we have used in Ref. [5]. For each BL Lac, we divide the sphere into concentric rings (bins) with fixed angular size. We count the number of events falling into each bin and then sum over all BL Lacs, thus obtaining the numbers N_i (data counts). We repeat the same procedure for a large number (typically 10^6) of randomly generated sets of UHECR events. This gives the mean Monte-Carlo counts N_i^{MC} , the variance σ_i^{MC} and the probability $p(\delta)$ to match or exceed the data count observed in the first bin. This probability is a function of the bin size δ . Peaks of $(N_i - N_i^{\text{MC}})/\sigma_i$ or minima of $p(\delta)$ with respect to δ show angular scales at which correlations are most significant.

The Monte-Carlo events are generated in the horizon reference frame with the geometrical acceptance

$$dn \propto \cos \theta_z \sin \theta_z d\theta_z,$$

where θ_z is the zenith angle. Coordinates of the events are then transformed into the equatorial frame assuming random arrival time. This transformation depends on the latitude of the experiment, so events simulating different experiments are generated separately. The distribution of the generated Monte-Carlo events in declination and right ascension reproduces well that of the experimental data.

We have shown in Ref. [5] that autocorrelations are most significant for the two sets of UHECR events: 26 Yakutsk events with energy $E > 2.4 \cdot 10^{19}$ eV and 39 AGASA events with energy $E > 4.8 \cdot 10^{19}$ eV. If BL Lacs are sources of UHECR, their correlations with UHECR should be particularly large for these two sets. Assuming that energies of the events are not important for correlations at small angles, we combine them together in one set of 65 events.

Since acceleration of particles to energies of order 10^{20} eV typically requires extreme values of parameters, probably not all BL Lacs emit UHECR of required energy. We assume that this ability is correlated with

optical and radio emissions, and select the most powerful BL Lacs by imposing cuts on redshift, apparent magnitude and 6 cm radio flux. For more than a half of BL Lacs the redshift is not known. It is generally expected that these BL Lacs are at $z > 0.2$. We include them in the set. The cuts

$$\begin{aligned} z > 0.1 \text{ or unknown; } \text{mag} < 18; \\ \text{energy flux at 6 cm wavelength } F_6 > 0.17 \text{ Jy} \end{aligned} \quad (1)$$

leave 22 BL Lacs which are shown in Fig.1 together with

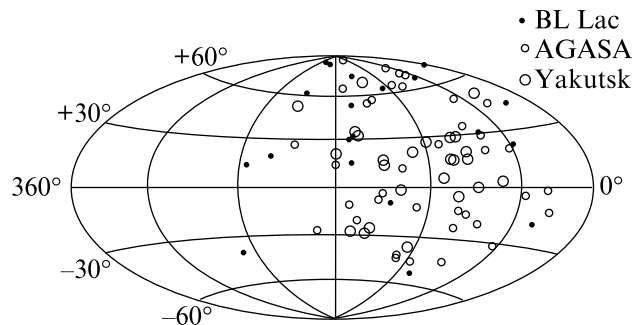


Fig.1. The sky map (in Galactic coordinates) with 65 UHECR events (circles) and BL Lacertae objects with cuts (1)

65 cosmic rays from the combined set. The dependence on cuts is discussed below.

As one can see from Fig.1, two of 22 BL Lacs coincide with the two triplets of UHECR events, one coincides with a doublet and two BL Lacs lie close to single events. This is reflected in the correlation function, which is plotted in Fig.2 for the bin size 2.5° . It has 8 events in the first bin while 1.25 is expected for the uniform distribution. The probability of such an excess is $2 \cdot 10^{-5}$. BL Lacs and UHECR events which contribute to this correlation are listed in Table. Note that at large angles the correlation function fluctuates around zero, which shows that the acceptance in the Monte-Carlo simulation is chosen correctly.

Names and coordinates (Galactic longitude, latitude and redshift) of BL Lacs plotted in Fig.1 which fall within 3° from some UHECR event (their energies are listed in the last column)

Name	l	b	z	$E/10^{19}$ eV
1ES 0806+524	166.25	32.91	0.138	3.4; 2.8; 2.5
RX J10586+5628	149.59	54.42	0.144	7.76; 5.35
2EG J0432+2910	170.52	-12.6	-	5.47; 4.89
OT 465	74.22	31.4	-	4.88
TEX 1428+370	63.95	66.92	0.564	4.97

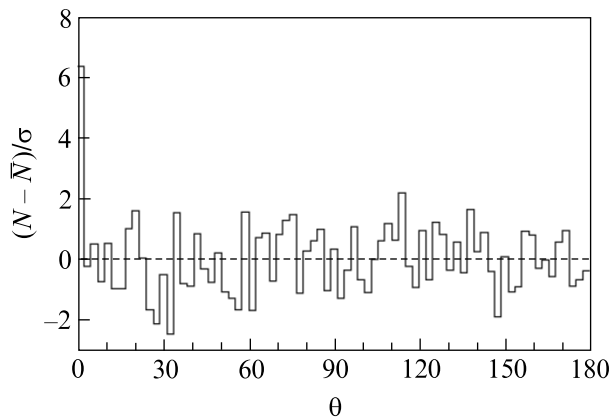


Fig.2. The angular correlation function between the combined set of UHECR and BL Lac set (1)

The probability $p(\delta)$ as a function of the angular separation δ is shown in Fig.3. It has a minimum at 2.5° . For comparison, smooth curve shows the behavior expected when 9 events out of 65 come from BL Lacs (assuming that accuracy of angle determination is 1.8° and distribution of errors is Gaussian).

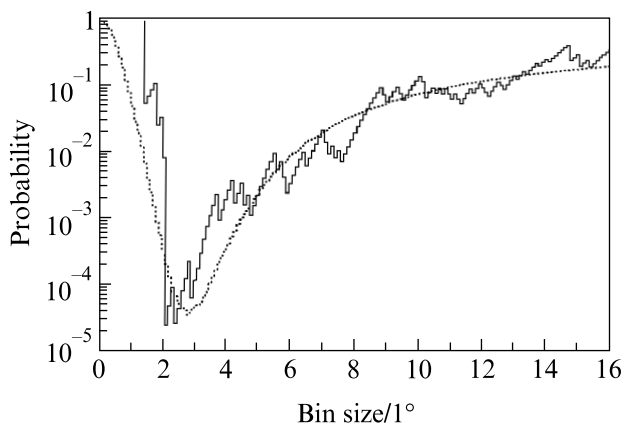


Fig.3. The dependence of the probability $p(\delta)$ on the bin size δ for the combined set of UHECR and BL Lac set (1)

The small angular size of the peak in the correlation function, compatible with the experimental angular resolution, suggests that UHECR events responsible for these correlations are produced by neutral primary particles. Indeed, if the primaries were charged they would have been deflected in the Galactic magnetic field by $3^\circ - 7^\circ$ depending on arrival direction, particle energy and the model of the magnetic field, and correlations at 2.5° would be destroyed.

Discussion. We have seen that 22 bright BL Lacs and 65 cosmic rays from the combined set are strongly correlated: the probability to find 8 or more out of 65 randomly generated cosmic rays within 2.5° of any of

the BL Lacs is $2 \cdot 10^{-5}$. Should one conclude that BL Lacs are sources of UHECR, or the above correlation may be an artifact of our selection procedure? Let us discuss possible loopholes.

First potential source of problem is incompleteness of the BL Lac catalog and non-uniform coverage of the sky. Indeed, 22 BL Lacs selected by cuts (1) almost all lie in the Northern hemisphere due to observational bias. However, it is easy to understand that, unlike for many other astrophysical problems, for establishing the *fact of correlations* with UHECR the incompleteness of BL Lac catalog is not essential. The method we use works for any set of potential sources regardless of their distribution over the sky (including such extreme cases as just one source, or a compact group of several sources). This is guaranteed by using the same set of sources with real data and with each Monte-Carlo configuration.

Second potential problem is related to the fact that there exist strong autocorrelations in the UHECR set, while Monte-Carlo events are not correlated. One may wonder if the observed correlation with BL Lacs is (partially) due to autocorrelations of UHECR. To see that this effect is negligible in our case, we performed test Monte-Carlo simulations with configurations containing the same number of doublets and triplets as the real data, and random in other respects. We found practically no difference between the two methods.

Finally, there is an issue of cuts and related issue of selection of catalogs. One may worry that by adjusting several cuts and searching in several catalogs the probability as small as $p_{\min} \sim 10^{-5}$ can be found with any set of astrophysical objects, even with those which have nothing to do with UHECR. So, the question is how easily the low values of p_{\min} can be obtained within the adopted procedure of cuts. This question can be studied quantitatively by assigning a proper penalty for each try in such a way that resulting probability gives true measure for the correlations in question to be a statistical fluctuation. For the case at hand we have found that when proper penalties are assigned, the resulting probability is larger than p_{\min} by about an order of magnitude. In other words, one would have to try thousands of catalogs to find correlation as significant as we have found for BL Lacs. We present the procedure of penalty calculation and resulting significance of correlations below.

In fact, we did not search for correlations with other catalogs of astrophysical objects. Thus, no penalty is associated with that. Similarly, we did not adjust the set of cosmic rays (as explained before, it was selected in Ref.[5] on the basis of most significant autocorrelations). But we do adjust cuts in the BL Lac catalog. Therefore, we should assign a penalty factor to this adjustment.

It is clear that some cuts have to be made because 65 events may have at most 65 sources among 306 BL Lacs in the catalog (probably much less). In our calculations we imposed cuts on redshift, magnitude and 6 cm radio-flux. The cut on redshift is motivated by the expected total number of sources; we did not adjust this cut to minimize the probability. Cuts on magnitude and radio-flux were adjusted. Corresponding penalty can be calculated in the following way (cf. Ref.[5]). A random set of cosmic rays should be generated and treated as real data, i.e. minimum probability p_{\min} is searched for by adjusting the cuts in the BL Lac catalog in exactly the same way as it was done for the real data. This should be repeated many times, giving different p_{\min} each time. The number of occurrences of a given value of p_{\min} is then calculated as a function of p_{\min} . This gives the probability (we call it p_{cor}) that the adjustment of the cuts in BL Lac catalog produces $p \leq p_{\min}$ with a random set of cosmic rays. The probability p_{cor} is a correct measure of the significance of correlations. We define $p_{\text{cor}}/p_{\min} > 1$ as the penalty factor.

We calculated p_{cor} with 10^5 random sets of cosmic rays. We have found that the penalty grows at small p_{\min} and approaches a constant value in the limit $p_{\min} \rightarrow 0$ (for this reason it is more convenient to define the penalty factor than to work in terms of p_{cor}). For the real set of UHECR $p_{\min} = 4 \cdot 10^{-6}$ and is reached with the cuts

$$z > 0.1 \text{ or unknown; } \text{mag} < 16; F_6 > 0.17 \text{ Jy.} \quad (2)$$

They leave 5 BL Lacs two of which coincide with triplets. (In the previous section different cuts are presented because, with similar significance, they include more potential sources.) This probability should be multiplied by the penalty factor. We found that the penalty factor is $\simeq 15$ at $p_{\min} \simeq 10^{-6}$ ¹⁾. This gives $p_{\text{cor}} = 6 \cdot 10^{-5}$, which is the probability that the correlation we have found is a statistical fluctuation.

Conclusions. The significant correlations between UHECR and BL Lacs imply that at least some of BL Lacs are sources of UHECR. Most probable candidates can be seen in Fig.1 and are listed in Table. Two BL Lacs, 1ES 0806+524 and RX J10586+5628, coincide with triplets of UHECR events (in the second case the third event of a triplet is at 4.5° and is not listed in the table). Both of them are at the distance of ~ 600 Mpc from the Earth. The next-probable candidate 2EG J0432+2910 has unknown redshift.

¹⁾This number does not include penalty for the adjustment of the bin size because minimum of $p(\delta)$ is consistent with the angular resolution. Corresponding factor is ≈ 4 .

The correlations at small angles are difficult to explain by charged primary particles. Within the Standard Model the only two neutral candidates are photon and neutrino. Photon attenuation length at $E < 10^{20}$ eV is much smaller (see e.g. [9]) than the distance to even the closest BL Lac. However, photons can not be ruled out yet if one assumes sources at $d \sim 600$ Mpc and “extreme” astrophysical conditions: primary particles accelerated to $E > 10^{23}$ eV with “hard” spectrum $\sim E^{-\alpha}$ and $\alpha < 2$, and extragalactic magnetic fields $B < 10^{-11}$ G [12]. Neutrino models [13] require similar assumptions except that constraints on the magnetic field are relaxed for “pure” neutrino sources and there is no constraint on the distance to the sources. However, if “pure” neutrino sources cannot be arranged, the model effectively becomes “photonic” [12]. If astrophysical difficulties can be overcome, these models will be appealing candidates for the solution of the UHECR puzzle. Alternatively, one may resort to a new physics, e.g., violation of the Lorentz invariance [14].

Independent cross-checks are necessary to determine whether particular objects are sources of UHECR. One of these cross-checks could be coincidence of arrival time of events contributing to small angle correlations with periods of activity of candidate BL Lacs. Dedicated monitoring of these BL Lac may be suggested. It is also important to analyze possible specific properties of air showers initiated by these events.

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