

## Compact sources of UHECR

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**Abstract.** We find significant autocorrelations at small angles corresponding to the experimental resolution in the data sets of UHECR observed by AGASA and Yakutsk experiments. We search for astrophysical sources which can be responsible for these autocorrelations and find significant correlations with BL Lacertae at small ( $\sim 2^\circ$ ) and large ( $3^\circ - 10^\circ$ ) angles. This suggests that both neutral and charged UHECR components are associated with BL Lacertae.

### 1 Introduction

Identification of sources of Ultra-High Energy Cosmic Rays (UHECR) is extremely important. Knowing their production sites will help to explain the absence of Greisen (1966), Zatsepin and Kuzmin (1966) (GZK) cut-off by selecting a particular class of models. In case of astrophysical origin it will give an invaluable information on physical conditions and mechanisms which may lead to acceleration of particles to energies higher than  $10^{20}$  eV. In 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.

Clustering of UHECR events at small angles (Chi et al., 1992; Efimov and Mikhailov, 1994) provides a very important hint on their origin. The AGASA collaboration has reported three doublets and one triplet out of 47 events with energies  $E > 4 \times 10^{19}$  eV, with chance probability of less than 1% in the case of the isotropic distribution (Takeda et al., 1999). The world data set has also been analyzed; 6 doublets and 2 triplets out of 92 events with energies  $E > 4 \times 10^{19}$  eV were found with the chance probability less than 1% (Uchi-hori et al., 2000).

Our recent analysis (Tinyakov and Tkachev, 2001a) based on the calculation of angular correlation function shows that explanation of clusters by chance coincidence is highly improbable: the probability of the fluctuation is  $4 \times 10^{-6}$ , see

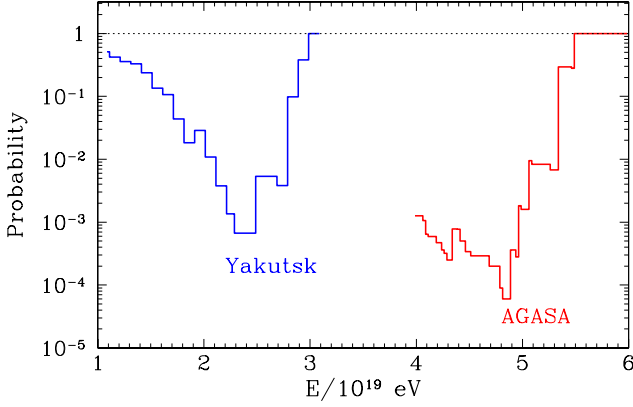
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Section 2. The natural strategy in searching for cosmic ray sources in this situation would be the following: 1) select UHECR data set where autocorrelations are largest; 2) try to identify sources using this particular cosmic ray data set. Pursuing this strategy we restrict ourselves to astrophysical sources with physical conditions potentially suitable for particle acceleration to highest energies.

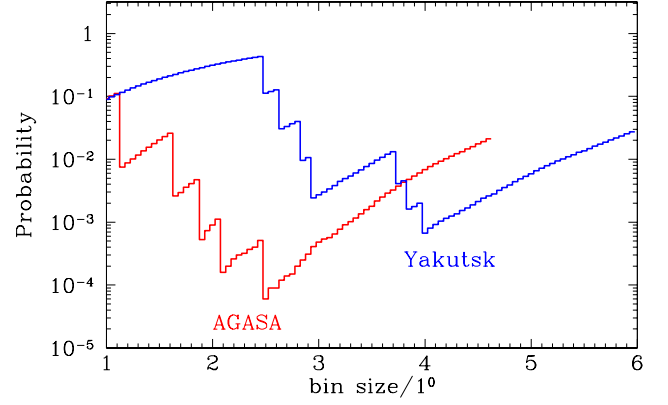
Active galactic nuclei (AGN) constitute particularly attractive class of potential sources. If AGNs are sources, those which have jets directed along the line of sight, or blazars, should correlate with observed UHECR events (regardless of the distance to a blazar in a world without GZK cut-off). Blazars include BL Lacertae and violently variable quasars with flat and highly polarised spectra (these spectral features give direct indication of seeing a relativistically beamed jet very close to the line of sight). BL Lacertae is a subclass of blazars characterised, in addition to the above, by the (near) absence of emission lines in the spectra. This might indicate low density of ambient matter and therefore especially favourable conditions for acceleration to high energies. We found that correlations with BL Lacertae do exist and are statistically significant (Tinyakov and Tkachev, 2001b), see Section 3.

### 2 Autocorrelation function of UHECR

The two-point correlation function for a given set of events is defined as follows. For each event, we divide the sphere into concentric rings (bins) with fixed angular size (say, the angular resolution of the experiment). We count the number of events falling into each bin, sum over all events and divide by 2 to avoid double counting, thus obtaining the numbers  $N_i$ . We repeat the same procedure for a large number (typically  $10^5$ ) of randomly generated sets (taking into account acceptance of experimental installations). This gives the mean Monte-Carlo counts  $N_i^{\text{MC}}$ , the variance  $\sigma_i^{\text{MC}}$  and  $p(\delta)$ , the latter is the probability to match or exceed the data count observed in the first bin as a function of the bin size  $\delta$



**Fig. 1.**  $p(\delta)$  with  $\delta = 2.5^\circ$  and  $\delta = 4^\circ$  for AGASA and Yakutsk data sets respectively as a function of energy.



**Fig. 2.**  $p(\delta)$  as a function of the bin size. Cuts in energy correspond to minima of Fig. 1.

assuming random distribution of arrival directions.

If clusters at highest energies are not a statistical fluctuation, one should expect that the spectrum consists of two components, the clustered component taking over the uniform one at a certain energy. The cut at an energy at which the clustered component starts to dominate should give the most significant signal. Motivated by these arguments, we calculated the probability of chance clustering as a function of energy cut. We present here the results for the AGASA (Takeda et al., 1999; Hayashida et al., 2000) and Yakutsk (Efimov N. N. et al., 1988) data sets (other experiments are discussed later). For these simulations we took the bin size equal to  $2.5^\circ$  and  $4^\circ$  for AGASA and Yakutsk, respectively, which is the quoted angular resolution of each experiment multiplied by  $\sqrt{2}$ . The results are summarized in Fig. 1, which shows the probability to reproduce or exceed the observed count in the first bin, as a function of the energy cut. AGASA curve starts at  $E = 4 \times 10^{19}$  eV because the data at smaller energies are not public. Yakutsk has much lower statistics. Both curves rapidly rise to 1 in a similar way when the statistics becomes poor. They suggest that the optimum energy cut is higher than can be imposed at present statistics.

We now turn to the determination of the angular size of the sources. To this end we calculate the dependence of the probability to have the observed (or larger) number of events in the first bin on the bin size. This dependence is plotted in Fig. 2. Jumps in the curves occur when a new doublet enters the first bin. Despite fluctuations, one can see that the minimum probability corresponds roughly to  $2.5^\circ$  and  $4^\circ$  for AGASA and Yakutsk, respectively. These numbers coincide with the angular resolutions of the experiments, as is expected for sources with the angular size smaller than the experimental resolution. Remarkably, there are no doublets in the AGASA set with separations between  $2.5^\circ$  and  $5^\circ$ , while for the the extended source of the uniform luminosity one would expect 4 times more events within  $5^\circ$  as there are within  $2.5^\circ$ . Thus, we conclude that the data favor compact sources with angular size less than  $2.5^\circ$ .

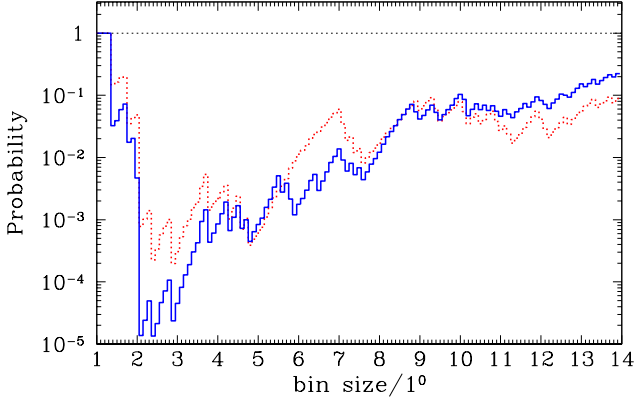
The other two UHECR experiments, Haverah Park (HP)

and Volcano Ranch (VR), do not see significant clustering. With the energy cut  $E > 2.4 \times 10^{19}$  eV and the bin size  $4^\circ$ , the HP data contain 2 doublets at 1.8 expected, while VR data contain 1 doublet at 0.1 expected with isotropic distribution. Let us estimate the combined probability of clustering in all experiments assuming independent Poisson distributions. The number of observed doublets in AGASA and Yakutsk data are 6 and 8, respectively, while 0.87 and 2.2 are expected (these expected numbers of doublets include “penalty” for the energy scan). Thus, 17 doublets are observed at 4.97 expected, which corresponds to the Poisson probability  $2 \times 10^{-5}$ . If HP data are excluded, the probability becomes  $1 \times 10^{-6}$ , while with both HP and VR data excluded the probability is  $4 \times 10^{-6}$ .

It is extremely unlikely that the clustering observed by AGASA and Yakutsk experiments is a result of a random fluctuation in an isotropic distribution. Rather, the working hypothesis should be the existence of some number of compact sources which produce the observed multiplets. Is this hypothesis consistent with HP and VR data? For a given experiment, the expected number of clusters is determined by the total number of events (Dubovsky et al., 2000); at small clustering it scales like  $N_{\text{tot}}^{3/2}$ . Taking AGASA data as a reference (6 doublets observed, 5.4 expected from sources and 0.6 expected from chance clustering) allows to estimate the expected number of doublets in other experiments by adding the doublets expected from sources and the doublets expected from the uniform background (calculated in the Monte-Carlo simulation). The results are summarized in Table 2, together with corresponding Poisson probabilities. All experiments are roughly consistent with the assumption that

**Table 1.**

|         | $N_{\text{tot}}$ | observed | expected    | probability |
|---------|------------------|----------|-------------|-------------|
| AGASA   | 39               | 6        | $5.4 + 0.6$ | —           |
| Yakutsk | 26               | 8        | $2.9 + 1.6$ | 0.09        |
| HP      | 32               | 2        | $4.0 + 1.8$ | 0.07        |
| VR      | 10               | 1        | $0.7 + 0.1$ | 0.55        |



**Fig. 3.** Solid line shows  $p(\delta)$  as the function of the bin size for the combined set of UHECR and BL Lac set (1). Dotted line is the same, but for AGASA events only.

the number of sources is such that they produce 5.4 doublets out of 39 events in average.

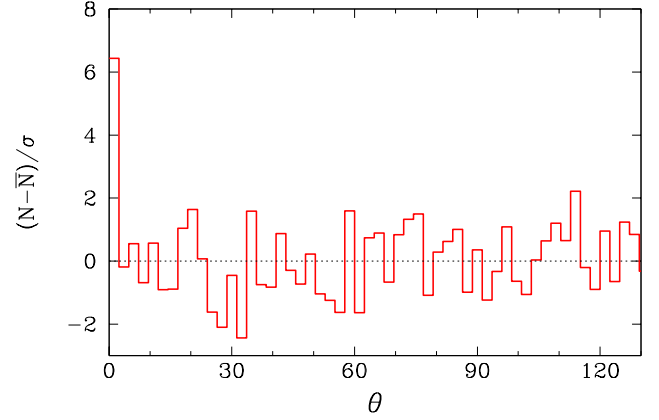
According to our simulations, the mean numbers of chance doublets are 0.6 and 1.6 for AGASA and Yakutsk, respectively. Therefore, most of the clusters in AGASA and Yakutsk data are likely to be due to real sources. The set of AGASA events with  $E > 4 \times 10^{19}$  eV and Yakutsk events with  $E > 2.4 \times 10^{19}$  eV is a suitable choice for the search of correlations with astrophysical objects.

### 3 Correlations with BL Lacertae

If AGNs are sources of UHECR, one can expect correlations of BL Lacs with observed events to be particularly large for the above two sets of events. The most recent catalogue of AGNs and quasars contains 306 confirmed BL Lacs (Veron-Cetty and Veron, 2000). Although this catalogue may be incomplete, this is not crucial for establishing correlations between BL Lacs and UHECR events. We impose certain cuts on BL Lac catalogue.

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 Dubovsky et al. (2000) to be of order several hundred. At energies below the GZK cut-off (or if the cutoff is absent), 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  $z \sim 0.1$ .

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 optical and radio emissions are correlated with this ability and select the most powerful BL Lacs by imposing cuts on redshift, apparent magnitude and 6 cm radio flux. For roughly half of BL Lacs the redshift is not known. It is generally expected that these BL Lacs are at  $z > 0.2$ . Therefore,



**Fig. 4.** The angular correlation function between the combined set of UHECR and BL Lac set (1).

we include them in the set. The resulting cuts are

$$z > 0.1 \text{ or unknown; } \text{mag} < 18; F_6 > 0.17 \text{ Jy} . \quad (1)$$

For the combined set of 65 UHECR events and BL Lac set (1) the probability  $p(\delta)$  as a function of the bin size is shown in Fig. 3. It has a minimum at  $2.5^\circ$  consistent with the resolution of AGASA and Yakutsk experiments ( $\sim 1.8^\circ$  and  $\sim 3^\circ$ , respectively).

The correlation function for the bin size  $2.5^\circ$  is shown in Fig. 4. It has a large excess in the first bin. The probability for such an excess to occur in the case of randomly distributed UHECR events is  $2 \times 10^{-5}$ . BL Lacs and UHECR events which contribute to this correlation are listed in Table 2. 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.

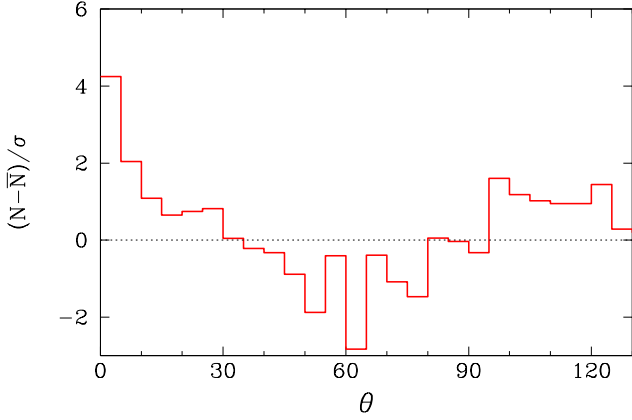
The small angular size of the peak in the correlation function, compatible with the experimental angular resolution, suggests that UHECR events responsible for these correlations are produced by neutral primary particles. Indeed, if the primaries were charged they would have been deflected in the Galactic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

It is important to note that making the cut on magnitude more restrictive,

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

**Table 2.** Names and coordinates (Galactic longitude, latitude and redshift) of BL Lacs which have UHECR events (their energies are listed in the last column) within  $3^\circ$  circle.

| 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. 5.** The correlation function between AGASA set and BL Lac set (3).

leaves only 5 BL Lacs, two of which coincide with triplets. With these 5 objects, the probability of coincidence is  $8 \times 10^{-6}$ . The fact that the probability is similar despite significantly different number of BL Lacs shows that there is no sharp dependence on cuts.

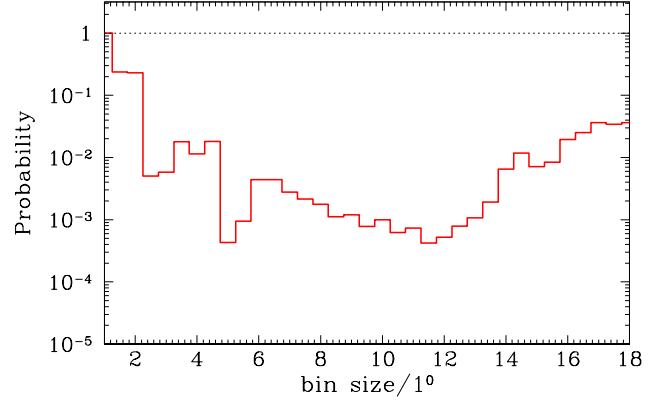
Correlation with BL Lacs suggests the acceleration origin of UHECR. Therefore, charged component (protons) may be present. Protons would be deflected in Galactic and extragalactic magnetic fields and would lead to correlations at larger angles unless extragalactic magnetic fields are extremely strong. To search for correlations between UHECR and BL Lac at larger angles it may not be correct to combine the two sets of events with different energies together. Since the average deflection angle is inversely proportional to energy, correlations should be larger in the high-energy set, while the addition of low-energy events may only “dilute” them and make insignificant. To avoid such a dilution, we remove the Yakutsk events from the set and consider only 39 AGASA events. With the set of cuts (1) and 39 AGASA events the excess is already significant:  $p(\delta)$  stays at the level of  $10^{-3}$  in the range  $2^\circ < \delta < 5^\circ$ . To see how this depends upon cuts we enlarge the set of BL Lacs by relaxing the cut on radio-flux, so that the cuts read

$$z > 0.1 \text{ or unknown; } \text{mag} < 18; F_6 > 0.025 \text{ Jy.} \quad (3)$$

This set of BL Lacs contains 80 objects. The correlation function of the AGASA set with these BL Lacs at the bin size  $5^\circ$  is shown in Fig. 5. Unlike the case of Fig. 4, the correlation function of Fig. 5 has a large-scale structure.

The probability  $p(\delta)$  as a function of the bin size  $\delta$  is shown in Fig. 6. It reaches a minimum value of  $3 \times 10^{-4}$  around  $12^\circ$  which is definitely larger than the experimental angular resolution. Remarkably, correlations are below 1% all the way from  $5^\circ$  to  $15^\circ$ .

The correlations at large angles are most naturally explained by assuming that (some of the) primary particles are charged and are deflected in Galactic and random extragalactic magnetic fields. Small angle correlations are difficult to explain if primary particles are charged. Within the Standard Model



**Fig. 6.** The dependence of the probability  $p(\delta)$  on the bin size  $\delta$  for AGASA set of UHECR and BL Lac set (3).

two stable neutral particles exist, photon and neutrino, but both are problematic. Photon attenuation length is much smaller than the distance to even closest BL Lac. Neutrino annihilation on the background  $\nu$ 's within GZK sphere may produce picture consistent with our findings (annihilation products contain both photons and protons), but neutrinos are difficult to produce in sufficient amounts, although at present the situation remains controversial (for a review see Weiler (1999)). With the exclusion of these candidates one will be forced to search for a new physics.

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