Clustering of UHECR and their sources

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(Received October 19, 2001)

We calculate angular correlation function of ultra-high energy cosmic rays. In the AGASA and Yakutsk data sets we find significant auto-correlations at angles compatible with the experimental angular resolution. We then look for correlations of these two sets with BL Lacertae objects (AGNs with jets directed along the line of sight). We find correlations at 2.5 degrees with chance probability 2×10^{-5}, and correlations at larger angles with somewhat lower significance. Our results suggest the existence of a neutral primary particle which is not attenuated due to interactions with CMB.

KEYWORDS: ultra-high energy cosmic rays, angular correlation function, BL Lacertae

§1. Introduction

The observed small-scale anisotropy[1,2] (clustering) of arrival directions of ultra-high energy cosmic rays (UHECR) is an extremely important feature. First, it may discriminate efficiently between existing models of UHECR. Some models, like those which assume diffusive propagation of UHECR in strong magnetic fields,[3] are not compatible with clustering; such models may be ruled out. The models based on the superheavy dark matter[4] may, in principle, explain clustering by clumping of the superheavy particles populating the halo. Such models may be strongly constrained. Even astrophysical models which naturally lead to clustering of UHECR events are constrained by statistical properties of clustering.[5]

Second, clustering suggests the existence of neutral primary particles which are not deflected in magnetic fields during propagation. This requirement is very restrictive as there are only 2 stable neutral particles in the Standard Model, photon and neutrino. It may constrain possible models even further.

Finally, clustering may help to identify the sources of UHECR since the events in clusters are more likely to look back to their source. The latter is extremely important. Knowing the production sites of UHECR will help to explain the absence of the Greisen-Zatsepin-Kuzmin (GZK) cutoff.[6] 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 and higher. 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.

Previous analyses[1,2,7] did not attempt to determine the distribution of clusters in angular size and therefore do not allow to address the first two of these issues. Here we use a different approach[8,9] based on the calculation of the angular correlation function. Our purpose is to determine whether clustering is statistically significant, calculate angular correlation function, find the subset of cosmic rays in which clustering is most significant and, making use of that subset, identify the sources of UHECR which are responsible for clusters.

§2. The method

We use the same method based on the calculation of the angular correlation function for studying both self-correlations of UHECR and their correlations with potential sources. 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 $10^5 - 10^6$) of randomly generated sets and calculate the mean Monte-Carlo value $N_i^{\rm MC}$ and the variance $\sigma_i^{\rm MC}$ for each bin in a standard way. The correlation function is defined as $f_i = N_i/N_i^{\rm MC} - 1$. A deviation of f_i from zero indicates the presence of correlations on the angular scale corresponding to i-th bin. The procedure is the same in the case of cross-correlations with sources except for the factor 2.

The correlation function f_i fluctuates. In order to see whether its deviation from zero is statistically significant, we define the ratio $(N_i - N_i^{\rm MC})/\sigma_i^{\rm MC}$, which shows the excess in the correlation function as compared to the random distribution in the units of the variance. With enough statistics, this quantity is a good measure of the probability of the corresponding fluctuation.

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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. We restrict our analysis to the events with zenith angles $\theta_z < 45°$ for which the experimental resolution of arrival directions is the best.[7] The distribution of the generated Monte-Carlo events in declination reproduces well that of the experimental data.

As a quantitative measure of correlations we use the probability $p(\delta)$ defined as follows. In the real data, we count the number $N(\delta)$ of pairs with angular separation less or equal δ. The same quantity is calculated for each of the Monte-Carlo sets, and the number of sets for which it matches or exceeds that for the data is counted. The probability $p(\delta)$ is determined by dividing the resulting count by the total number of sets. The minima of $p(\delta)$ with respect to δ show at which angles correlations are most significant. Note that other probabilities may be defined and measured in this way, provided the same quantity is calculated for the real data and for each of the random sets.

§3. Autocorrelations of UHECR

If clusters observed at highest energies are not a statistical fluctuation, one may 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 this argument, we calculated the probability of chance clustering as a function of energy cut for the AGASA[2] and Yakutsk[10] data sets (other experiments are discussed below). For these simulations we took the angular size $\delta = 2.5°$ and $\delta = 4°$ for AGASA and Yakutsk, respectively, which is the quoted (see e.g.[2,7]) angular resolution of each experiment multiplied by $\sqrt{2}$. The results are shown in Fig. 1. AGASA curve starts at $E = 4 \times 10^{19}$ eV because the data at smaller energies are not available. Yakutsk has much lower statistics. Both curves rapidly rise to 1 in a similar way when the statistics becomes poor. This behavior suggests that the optimum energy cut is higher than can be imposed at present statistics.

Correlation functions calculated with the energy cuts corresponding to the lowest chance probability ($E > 2.4 \times 10^{19}$ eV and $E > 4.8 \times 10^{19}$ eV for Yakutsk and AGASA, respectively) are shown in Figs. 2 and 3. Both AGASA and Yakutsk correlation functions have substantial excess in the first bin. The peak in AGASA curve corresponds to 6 doublets of which 3 actually form a triplet. The peak in Yakutsk curve corresponds to 8 doublets of which 3 also form a triplet.

As the lowest probabilities were obtained by scanning over the energy, one may argue that they have to be

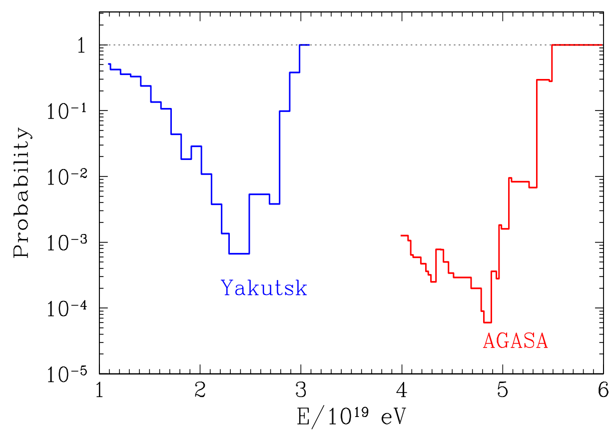

Fig. 1. Probability $p(\delta)$ as a function of the energy cut. The angle δ is taken 2.5° for the AGASA curve and 4° for the Yakutsk curve.

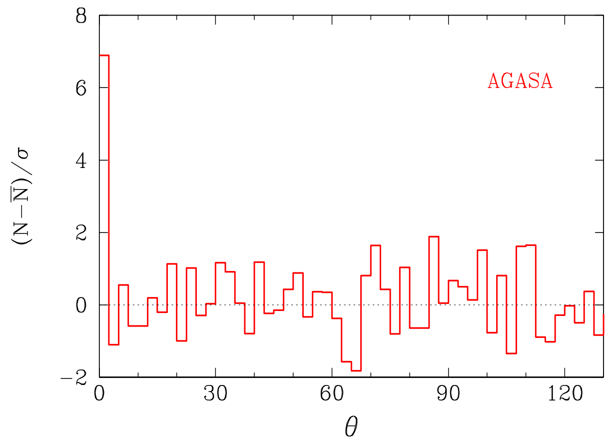

Fig. 2. Angular correlation function of AGASA events with $E > 4.8 \times 10^{19}$ eV.

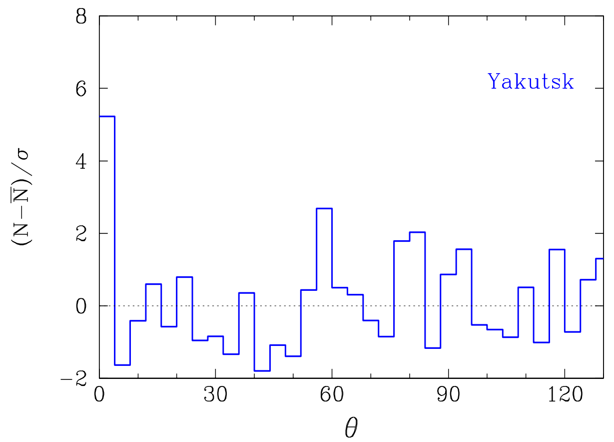

Fig. 3. Angular correlation function of Yakutsk events with $E > 2.4 \times 10^{19}$ eV.

multiplied by the number of steps in the scan. This is not correct because the results at different energy cuts are not independent: higher energy set is a subset of the lower energy one. As can be seen from Fig. 1, the chance probability for AGASA is lower than 10^{-3} in the whole energy range $(4-5)\times 10^{19}$ eV, regardless of the number of steps in the scan. There still may be a correction factor. To estimate it we made the following numerical experiment. For 10^3 randomly generated sets of events we have performed exactly the same procedure as for the real data, i.e. scanned over energies and obtained 10^3 different minimum probabilities. We found that the probability less than 10^{-2} occurred 27 times, while the probability less than 10^{-3} occurred 3 times. Thus we conclude that the correction factor is of order 3. This factor is included in the final results which are presented in Table. I.

Table I. Summary of auto-correlations in AGASA and Yakutsk data sets.

experiment	angle	$E_{\rm min}$	probability of chance clustering
AGASA	2.5°	4.8×10^{19} eV	3×10^{-4}
Yakutsk	4°	2.4×10^{19} eV	2×10^{-3}

We now turn to determination of the angular size of the sources. To this end we calculate the probability $p(\delta)$ as a function of δ. The result is shown in Fig. 4. Jumps in the curves occur at the angular separation of

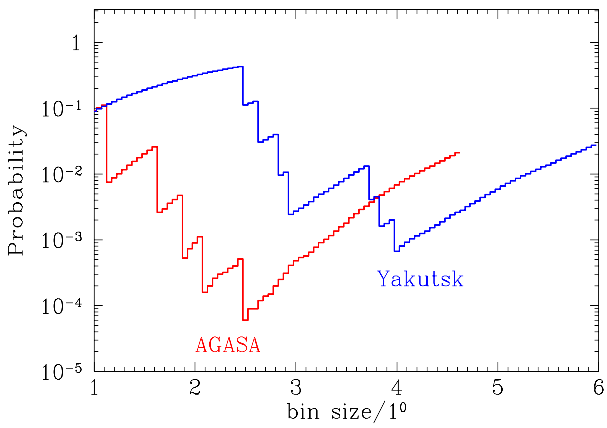

Fig. 4. The probability $p(\delta)$ as a function of the bin size δ. Cuts in energy correspond to minima of Fig. 1.

each doublet. Despite fluctuations, one can see that the minimum probability corresponds to roughly 2.5° and 4° 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° and 5°, while for the the extended source of the uniform luminosity one would expect 4 times more events within 5° as there are within 2.5°. Thus, we conclude that the data favor compact sources with angular size less than 2.5°.

The other two UHECR experiments, Haverah Park (HP) and Volcano Ranch (VR), do not see significant clustering.[11] With the energy cut $E > 2.4\times 10^{19}$ eV and the bin size 4°, the HP data contain 2 doublets at 1.8 expected, while VR data contain 1 doublet at 0.1 expected. 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 "effective" expected numbers of doublets are calculated from the condition that probabilities of Table 1 are reproduced, i.e. "penalty" for the energy scan is included). Thus, 17 doublets are observed at 4.97 expected, which corresponds to the Poisson probability 2×10^{-5}. If HP data are excluded, the probability becomes 1×10^{-6}, while with both HP and VR data excluded the probability is 4×10^{-6}.

The resulting small probabilities strongly suggest that clustering is due to the existence of a certain number of sources. Is this hypothesis consistent with HP and VR data? For a given set of sources the expected number of clusters is determined by the total number of events;[12,13] at small clustering it scales like $N_{\rm tot}^{3/2}$.[12] 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 II, together with corresponding Poisson probabilities. All experiments are roughly consistent with the assumption that the number of sources is such that they produce 5.4 doublets out of 39 events in average. Note that if HP data are discarded,[11] the agreement between other experiments can be made better.

Table II. Sample of half-text table.

	$N_{\rm tot}$	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

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. In the next section we identify some of these sources.

§4. Correlations with BL Lacertae objects

In search for sources of UHECR, 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.[14] and references therein) have been proposed. Possible connection of highest-energy cosmic rays with these objects was considered in Refs.[15–23] In this paper we study correlations of UHECR with BL Lacertae (BL Lac) objects. BL Lacs are characterized by "featureless" optical spectra, rapid aperiodic variability in all wavelengths and high (up to 40%) polarization of their optical continuum emission. These features are direct indication of seeing a relativistic jet very close to the line of sight.[24] BL Lacs are the rarest type of active galactic nuclei. The most recent catalog of AGNs and quasars contains 306 confirmed BL Lacs,[25] although this catalog may be incomplete.

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 roughly 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

$$z > 0.1 \text{ or unknown}; \quad \text{mag} < 18; \quad F_6 > 0.17 \text{ Jy} \qquad (4.1)$$

leave 22 BL Lacs. They are shown in Fig. 5 together with 65 cosmic rays from the combined set. The dependence

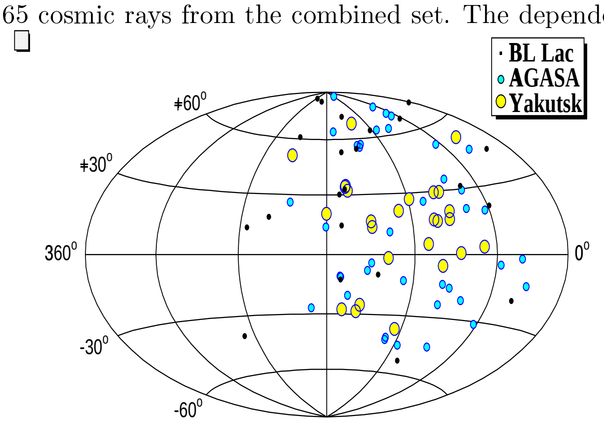

Fig. 5. The sky map (in Galactic coordinates) with 65 UHECR events (circles) and BL Lacertae objects with cuts (4.1).

on the cuts on magnitude and radio-flux is discussed below.

For the combined set of 65 UHECR events and BL Lac set (4.1) the probability $p(\delta)$ is shown in Fig. 6. It has a minimum at 2.5° consistent with the experimental angular resolution. The corresponding correlation function calculated with the bin size 2.5° is shown in Fig.7. It has a large excess in thefirst bin. The probability for such an excess to occur in the case of randomly distributed UHECR events is 2×10^{-5}. BL Lacs and UHECR events which contribute to this correlation are listed in Table III. 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

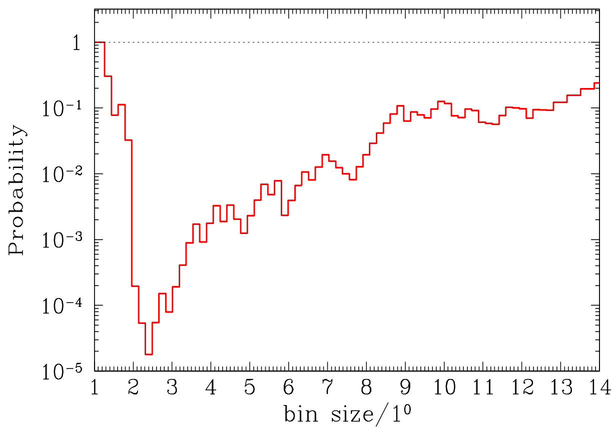

Fig. 6. The dependence of the probability $p(\delta)$ on the bin size δ for the combined set of UHECR and BL Lac set (4.1).

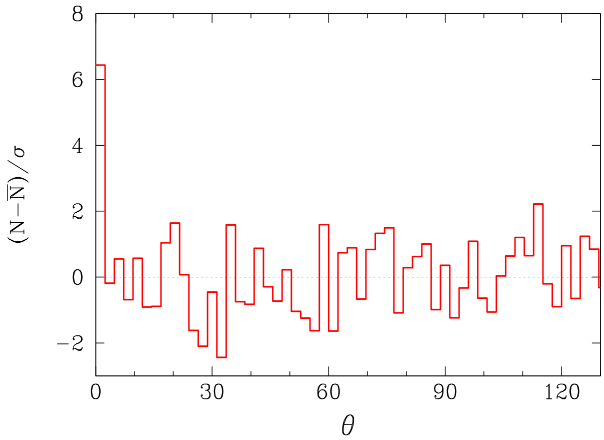

Fig. 7. The angular correlation function between the combined set of UHECR and BL Lac set (4.1).

Table III. Names and coordinates (Galactic longitude, latitude and redshift) of BL Lacs plotted in Fig. 5 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	32.9	0.138	3.4; 2.8; 2.5
RX J10586+5628	149.59	54.4	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	66.9	0.564	4.97

correlations are produced by neutral primary particles. Indeed, if the primaries were charged they would have been deflected in the Galactic magnetic field by $3° - 7°$ depending on arrival direction, particle energy and the model of the magnetic field. This would destroy correlations at 2.5°.

The correlations are even stronger for the brightest subset which is selected by making the cut on magnitude more restrictive,

$$z > 0.1 \text{ or unknown}; \quad \text{mag} < 16; \quad F_6 > 0.17 \text{ Jy}. \qquad (4.2)$$

These cuts leave only 5 BL Lacs two of which coincide with triplets. With these 5 objects, the probability of coincidence is 8×10^{-6}. The fact that the probability is similar despite different number of BL Lacs shows that correlations are not due to careful adjustment of cuts.

So far, our idea was to take the UHECR set with maximum auto-correlations and check if these sets of cosmic rays correlate with brightest BL Lacs. We have found that correlation are most significant when the cuts (4.1) and (4.2) on magnitude and radio-flux are imposed. Let us now discuss what happens if some of the cuts are relaxed and more BL Lacs are included in the set. The general trend is that correlations at small angles get diluted (although do not disappear completely). At the same time the behavior of $p(\delta)$ changes: its minimum shifts to larger angles and becomes wider. A possible interpretation of this effect may be the following. Correlation with BL Lacs suggests the acceleration origin of UHECR. Therefore, charged component (protons) may be present. Protons may be deflected in galactic and extragalactic magnetic fields and may lead to correlations at larger angles. Such correlations are more difficult to separate from the background; this is why they may not be seen in a small set of BL Lacs. If this interpretation is correct, the low-energy Yakutsk data should be excluded from the set when studying large-angle correlations.

As an example, consider correlations of AGASA set with the BL Lac set obtained by weakening the cut on the radio-flux,

$$z > 0.1 \text{ or unknown}; \quad \text{mag} < 18; \quad F_6 > 0.025 \text{ Jy}, \qquad (4.3)$$

which contains 80 objects. The probability $p(\delta)$ as a function of δ is shown in Fig. 8. It reaches a minimum value of 3×10^{-4} around 12°. Remarkably, correlations are below 1% all the way from 5° to 15°. Similar behavior

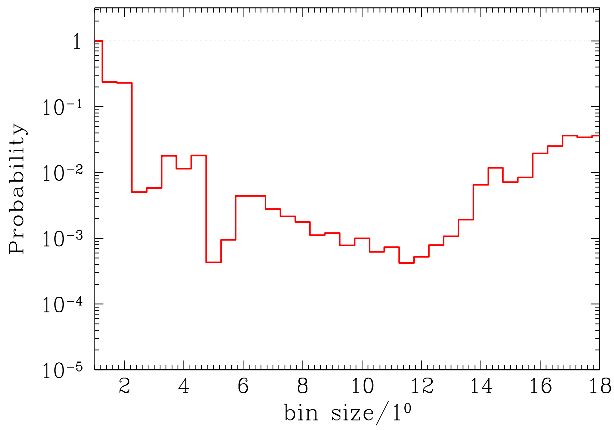

Fig. 8. The dependence of the probability $p(\delta)$ on the bin size δ for AGASA set of UHECR and BL Lac set (4.3).

of $p(\delta)$ is found for other large sets of brightest BL Lacs.

Correlations with BL Lacs are present and significant in other UHECR data sets as well. For instance, for the the independent set of AGASA events with energies $4 \times 10^{19} < E < 4.8 \times 10^{19}$ eV one finds both correlations at $\sim 2°$ with chance probability of 4×10^{-4} and at $8° - 10°$ with chance probability of 10^{-3}.

One may worry about probable incompleteness of the BL Lac catalog. However, it is not essential for establishing correlations with UHECR. 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 of the Monte-Carlo configurations.

The existing complete catalogs of BL Lacs contain much smaller number of objects than the catalog used above. These catalogs may be considered in the same way. The radio-selected BL Lac catalog[26)] is one suitable choice. There are no small-angle correlations with this catalog. However, large-angle correlations exist at the level below 1%. Another choice is the complete sample of X-ray selected BL Lacs presented in Ref.[27)] With the cuts (4.2), correlations of this catalog with the combined set of cosmic rays correspond to the probability of coincidence 1×10^{-5}. The detailed discussion of correlations with these and other sets of BL Lacs will be presented elsewhere.

Another issue one may worry about is *auto-correlations* the UHECR set. While in the real data auto-correlations are significant, the Monte-Carlo sets are random, and one may expect that this affects correlations with BL Lacs. That such an effect exists can be seen in the (hypothetical) extreme case when all cosmic rays coincide. In our case, however, this effect is negligible. To see this we have calculated the probability $p(\delta)$ with Monte-Carlo configurations containing certain number of doublets and triplets and random otherwise. With number of clusters the same as in the real data, the results are practically undistinguishable from the case of totally random configurations.

As a final check that correlations we have found are not an artifact of our procedure, we have studied by the same method the correlations between UHECR and compact radio-loud quasars from Kühr catalog.[28)] We see no significant correlations regardless of the cuts, in agreement with Ref.[20)]

§5. Conclusions

The significant correlations between UHECR and BL Lacs imply that some of BL Lacs are sources of UHECR. Most probable candidates can be seen in Fig. 5 and are listed in Table 1. 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 a distance of order $\sim$ 600 Mpc from the Earth. The next-probable candidate 2EG J0432+2910 has unknown redshift.

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[14)] is much smaller than the distance to even the closest BL Lac. Neutrino models have generic difficulties with production of sufficient flux of high energy neutrinos, although at present the situation is controversial.[29] If the difficulites can be overcome, these models will be an appealing candidate for the solution of the UHECR puzzle.

The correlations at large angles, on the contrary, may be naturally explained by assuming that (some of the) primary particles are charged and are deflected in random extragalactic magnetic fields. From this assumption one may deduce an estimate for the strength of the extragalactic magnetic fields. The formula for deflection angle reads[30]

$$\Delta\theta = 0.8^\circ \left(\frac{10^{20}\ \mathrm{eV}}{E}\right) \left(\frac{R l_c}{10\ \mathrm{Mpc}^2}\right)^{1/2} \left(\frac{B}{10^{-9}\ \mathrm{G}}\right),$$

where l_c is the correlation length of the field. Requiring $\Delta\theta = 10^\circ$ at $R = 1$ Gpc, $E = 5\times10^{19}$ eV and $l_c = 1$ Mpc gives for the field strength $B \sim 10^{-9}$ G. The accuracy of this estimate is poor; nevertheless, it may become a method to measure extragalactic magnetic fields in the future.

Because of the small probability of chance coincidence, we believe that the correlations between UHECR and BL Lacs are real. However, independent cross-checks are necessary, especially 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.

Acknowledgements

We are grateful to S.I. Bityukov, S.L. Dubovsky, A.A. Mikhailov, K.A. Postnov, V.A. Rubakov, M.E. Shaposhnikov, D.V.Semikoz and M. Teshima for valuable comments and discussions. This work is supported in part by the Swiss Science Foundation, grant 21-58947.99, and by INTAS grant 99-1065.

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