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Evidence for a connection between gamma-ray and highest-energy cosmic ray emissions by BL Lacs

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ABSTRACT

A set of potentially γ-ray loud BL Lacs is selected by intersecting the EGRET and BL Lac catalogs. Of the resulting 14 objects 8 are found to correlate with arrival directions of ultra-high energy cosmic rays (UHECR), with the significance of order 5σ. This suggests that γ-ray emission can be used as a distinctive feature of those BL Lacs which are capable of producing UHECR.

Subject headings: cosmic rays — BL Lacertae objects: general — gamma rays: theory

The highest-energy cosmic rays with energies in excess of 10^{19} eV (UHECR) observed by AGASA (Hayashida et. al. 1999) and Yakutsk (Afanasiev et. al. 1996) experiments, show a significant number of clusters at angles of the order of experimental angular resolution (Uchihori et. al. 2000). The significance of clustering is quantitatively estimated by calculating the angular correlation function of the UHECR events (Tinyakov & Tkachev 2001a). It follows that the observed clustering has probability $< 10^{-5}$ to occur as a result of a statistical fluctuation (Tinyakov & Tkachev 2001a). This suggests that *i)* there exist compact sources of UHECR and *ii)* the already existing data may contain information sufficient to identify

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the actual sources, the subset of cosmic rays with maximum autocorrelations being the best choice for this purpose.

This line of reasoning was pursued by Tinyakov & Tkachev (2001b) assuming that BL Lacertae objects (BL Lacs) are relevant candidates. Significant correlations were found with the subset of most powerful (confirmed) BL Lacs. After assigning penalties for subset selection and bin size adjustment, the probability of such correlation to occur by chance in a random distribution is of order 10^{-4} (Tinyakov & Tkachev 2001b). BL Lacs comprise a subclass of blazars which is characterized by the absence of emission lines. Blazars are thought to have relativistic jets directed along the line of sight, while the absence of emission lines indicates low ambient matter and radiation fields, and therefore favorable conditions for acceleration of particles to highest energies. For this reason BL Lacs were considered as particularly promising candidates for UHECR sources by Tinyakov & Tkachev (2001b).

It follows from both the statistical arguments (Dubovsky et. al. 2000) and correlation analysis (Tinyakov & Tkachev 2001b,c) that only a small fraction of existing BL Lacs should be capable of producing highest-energy cosmic rays. For understanding the nature of the sources, the key question is which physical characteristics singles out the actual UHECR emitters among all BL Lacs. In this letter we propose that the strong γ-ray emission is the feature which distinguishes UHECR sources.

There are general reasons to expect the connection between UHECR and γ-ray emissions. Both the acceleration of particles in the source and their subsequent propagation is accompanied by energy losses. A substantial part of this energy is transferred into the electromagnetic cascade and, generically, ends up in the EGRET energy region (Berezinsky et. al. 1990; Coppi & Aharonian 1996) either right in the source, or in the extragalactic space simply because the Universe is not transparent for γ-rays of higher energies. While the extragalactic cascade gets isotropized by random magnetic fields when approaching the low energy end, in some models which involve very high-energy photons (either directly (Kalashev et. al. 2001; Neronov et. al. 2002) or via Z-bursts mechanism (Weiler 1982; Fargion et. al. 1999)) the energy can be pumped from highest energies directly into the EGRET region thus preserving directionality. These arguments suggest that gamma ray emission may be an important distinctive feature of UHECR sources[8].

In order to test this hypothesis we first select those BL Lacs which can be associated with gamma ray sources, and then study their correlations with UHECR. The most complete list of the gamma ray sources can be found in the 3d EGRET catalog (Hartman et. al. 1999) containing 271 object. Of these objects, 67 are identified with AGNs, 5 with pulsars, 1 with

[8]We are grateful to A. Neronov and D. Semikoz for numerous useful discussions of this subject.

solar flare, 1 with LMC, and 27 are tentatively identified with AGNs. The remaining 170 objects are unidentified.

In this paper we do not rely on the existing EGRET identification of objects. Neither do we attempt our own object-by-object analysis. Instead, we adopt a purely statistical approach. Namely, we take the full set of confirmed BL Lacs from the Veron2001 catalog (Véron-Cetty & Véron 2001) consisting of 350 objects and select a subsample of those which may be associated with an EGRET gamma ray source.

The selection procedure is the following. Point sources in the EGRET catalog are defined as a local excess of a signal over the uniform background. Each source is associated with a contour containing 95% of the signal. For each contour, a circle of equal area is defined, with the radius R_{95}. These radii are listed in the EGRET catalog. They roughly correspond to uncertainties in the positions of sources. However, the 95% contours are often non-circular. Additional systematic errors in position determination may be present in the case of a bright nearby source (such cases are marked as "confused" in the catalog). As a result, many well-identified sources (e.g., Vela pulsar which is unambiguously identified by timing) fall outside of R_{95}. In our analysis, we consider an object to be associated with the EGRET source if the angular distance between the two does not exceed $2R_{95}$. In the case of ambiguity the nearest neighbor is taken.

According to this procedure, 14 BL Lacs from the Veron2001 catalog are associated with EGRET sources. They are listed in Table 1. Of these 14 objects, 8 already have identifications in the EGRET catalog, while 6 are newly proposed identifications. Out of 8 previously identified objects, 5 have the same identifications in the SIMBAD database as is suggested by our procedure (they are marked by star in the column 4 of Table 1). Interestingly, in those 3 cases when our procedure suggests identification different from the existing one, the latter has a question mark in the SIMBAD database, while in 5 cases when they coincide the existing identification is considered firm. This rather good agreement with previous results gives confidence that at least part of previously unidentified EGRET sources listed in Table 1 should be identified with corresponding BL Lacs.

The new identifications we propose in Table 1 result from our assumption that some BL Lacs are sources of gamma rays. This hypothesis is inspired by correlations between BL Lacs and highest-energy cosmic rays (Tinyakov & Tkachev 2001b), and possible relation between gamma ray and UHECR emissions. Since the EGRET 95% contours are large enough to contain several astrophysical objects, the identification depends on assumption about candidate sources. Most of previous works have concentrated on the powerful radio quasars as possible candidates (see, e.g., Mattox et. al. (2001)). An approach somewhat similar to ours was used by Punsly (1999) where correlations of EGRET catalog with X-

3EG J (1)	E ID (2)	Possible BLL (3)	(4)	l (5)	b (6)	z (7)	E (8)	Q (9)
0433+2908	A	2EG J0432+2910	*	170.5	-12.6		5.47; 4.89	0 or +1
0808+5114	a	1ES 0806+524	*	166.2	32.91	0.138	3.4; 2.8; 2.5	0
0812-0646	a	1WGA J0816.0-0736		229.8	14.96	0.04		
1009+4855	a	GB 1011+496		165.5	52.71 0.2			
1052+5718	a	RGB J1058+564	*	149.6	54.42	0.144	7.76; 5.35	0
1222+2841	A	ON 231	*	201.7	83.29	0.102		
1310-0517		1WGA J1311.3-0521		312.1	57.16	0.16		
1424+3734		TEX 1428+370		63.95	66.92	0.564	4.97	0 or +1
1605+1553	A	PKS 1604+159	*	29.38	43.41			
1621+8203		1ES 1544+820		116.5	32.97		2.7	+1
1733+6017		RGB J1742+597		88.46	31.78		2.5	+1
1850+5903		RGB J1841+591		88.68	24.29	0.53	5.8; 2.8	+1
1959+6342		1ES 1959+650		98.0	17.67	0.047	5.5	+1
2352+3752	a	TEX 2348+360		109.5	-24.91	0.317		

Table 1: List of BL Lacs associated with EGRET sources and UHECR which contribute to correlations.
Notes: (1) EGRET name; (2) EGRET identification: A - AGN, a - possible AGN; (3) possible BL Lac counterpart; (4) star marks cases when suggested BL Lac identification of the EGRET source agrees with SIMBAD database (2002); (5) and (6) Galactic coordinates of the BL Lac counterpart; (7) redshift of the BL Lac counterpart as given by Véron-Cetty & Véron (2001); (8) energies of correlating cosmic rays (4 sources correlate with more than one CR event) (9) UHECR charge assignments under which correlation occurs.

ray and moderate radio sources (RGB catalog) were considered. It revealed several new identifications, large fraction of them being BL Lacs.

Being based on position coincidence only, the identifications proposed in Table 1 cannot be considered as final. Instead, Table 1 should be treated as a starting point for more detailed object-by-object study including EGRET intensity maps, time correlations etc. Such an analysis goes beyond the scope of this paper. It is important to note, however, that possible mis-identifications in Table 1 do not compromise our main result, strong correlations of the selected subsample with UHECR. Like any random factor, such mis-identifications can only diminish the correlations.

Let us now turn to correlations between the set of 14 (potentially) γ-ray loud BL Lacs of Table 1 and UHECR. In the part concerning UHECR we follow the approach of Tinyakov & Tkachev (2001b) and use the set of cosmic rays with largest autocorrelations. This set consists of 39 AGASA events with energies $E > 4 \times 10^{19}$ eV and 26 Yakutsk events with energies $E > 2.4 \times 10^{19}$ eV (Tinyakov & Tkachev 2001a).

In the correlation analysis, we take into account possible effect of the Galactic magnetic field (GMF) on propagation of UHECR. We use the spiral model of GMF with different directions of the field in the two spiral arms, and opposite directions below and above the galactic disk. The details of the model and corresponding parameters can be found in Ref. (Tinyakov & Tkachev 2001c) together with further references. Since the effect of GMF depends on the assumption about charges of primary particles, we consider separately three cases: *i)* all cosmic rays are assumed to be neutral *ii)* all particles are assumed to have charge $Q = +1$ *iii)* each particle can have charge 0 or +1 depending on which possibility gives better correlation.

The numerical algorithm used in this paper is identical to that of Refs. (Tinyakov & Tkachev 2001a,b,c). We characterize the significance of correlations between UHECR and a given set of sources at a given angular scale δ by the probability $p(\delta)$ defined in the following way. First, we count the number of pairs source — cosmic ray separated by the angle $\leq \delta$ in the real data, thus obtaining the data count $N_d(\delta)$. We then generate a large number of random (mock) sets of cosmic rays, taking into account actual acceptance of the experiments in such a way that the large-scale distribution of mock cosmic rays is uniform. On small scales we introduce autocorrelations in mock sets since the real data are clustered. The amount of clusters added in each mock set mimics the real data, while cluster positions are random. For each mock set, the number of pairs source — cosmic ray is then counted in the same way as for the real data, giving the mock count $N_m(\delta)$. At large total number of mock sets, the fraction of mock sets for which $N_m(\delta) \geq N_d(\delta)$ gives $p(\delta)$.

In the case $Q = +1$ the positions of cosmic rays are corrected for the deflections in GMF prior to counting the number of pairs with given angular separation. In the case when both $Q = 0$ and $Q = +1$ are allowed, the two possible positions (original and corrected for GMF assuming charge +1) are considered for each cosmic ray. For a given ray, the minimum angular distance over the whole set of sources determines the actual charge assignment. In both cases, each mock set is subject to exactly the same procedure as the real data. This guarantees that no correlations are artificially introduced.

The results of the calculations in all three cases are shown in Fig. 1. The dotted, dashed, and solid curve represent cases $Q = 0$, $Q = 1$ and $Q = 0, +1$, respectively. First one notes that in all three cases the probability that correlations are due to a chance coincidence is well below 10^{-3}. While in the cases $Q = 0$ and $Q = +1$ the minimum probabilities are comparable, in the case of both charges the minimum of the probability is much lower and reaches the value of 3×10^{-7}, which formally corresponds to the significance 5.1σ. Second, in all three cases the probability has a minimum at angular scales $< 3^\circ$, comparable to the angular resolution of UHECR experiments. This is what is expected for compact sources of UHECR. In the case of $Q = 0$ the probability has low values up to $\sim 7^\circ$. This reflects the excess (as compared to the uniform distribution) of pairs BL Lac — cosmic ray with corresponding angular separations. This excess is due to cosmic rays which contribute to correlations at $\delta < 3^\circ$ after reconstruction in GMF in the case of $Q = 1$ (note that typical deflection in GMF is of order several degrees).

Energies and charges of UHECR events which contribute into correlations with γ-ray loud BL Lacs are listed in columns (8) and (9) of Table 1. The entry “0 or +1” in the 9th column means that the corresponding event contributes in both cases, $Q = 0$ and $Q = +1$. As follows from Table 1, only three cosmic rays contribute in both cases, while the rest are different. This explains why correlations improve substantially when both charges are allowed.

The comparison between Table 1 of this paper and Table 1 of Ref. (Tinyakov & Tkachev 2001b) shows that the same BL Lacs and cosmic rays contribute to correlations in Ref. (Tinyakov & Tkachev 2001b) and in the case of $Q = 0$ presented above. In Ref. (Tinyakov & Tkachev 2001b) the set of brightest BL Lacs was selected by imposing cuts on redshift, apparent magnitude and radio flux. In the resulting subset of 22 BL Lacs 5 candidate sources were identified. It is remarkable that 4 out of these 5 candidates, in particular all 3 which correlate with UHECR multiplets, are among 14 BL Lacs which comprise the intersection of BL Lac and EGRET catalogs, γ-ray loud BL Lacs. Even more remarkable is that out of 10 remaining BL Lacs 4 correlate with cosmic rays after correction for GMF. Among the remaining 6 which do not correlate with UHECR, 2 objects are situated in the Southern hemisphere invisible for Yakutsk and AGASA experiments. These objects can be excluded from correlation analysis. Thus, the majority of γ-ray loud BL Lacs (8 out of 12) correlate with UHECR. One concludes that the ability to emit gamma rays may be used as the physical criterion which allows to select actual UHECR sources from the complete set of BL Lacs.

BL Lacs are typically faint objects. Because of the absence of emission lines they often have unknown redshifts. Many of them may not yet be observed, or not identified as BL Lacs. Some BL Lacs, therefore, may be present among unidentified EGRET sources. If this is the case, one expects the latter to correlate with UHECR. To study this possibility we select two very similar subsets of EGRET sources: (1) unidentified sources with Galactic latitude $|b| > 10^\circ$ and (2) sources with unknown redshifts and Galactic latitude $|b| > 10^\circ$. The cut $|b| > 10^\circ$ is made to increase the fraction of extragalactic sources (according to Grenier (2000), the total number of extragalactic unidentified sources is expected to be 30-40). The subsets (1) and (2) contain 96 and 105 objects, respectively; they largely overlap. Both subsets correlate with UHECR.

The results of correlation analysis are shown in Fig. 2. Dotted and solid curves represent the probability $p(\delta)$ in the case of sets (1) and (2), respectively. In both cases the charge $Q = +1$ was assumed for all UHECR (in the case of $Q = 0$ correlations are weak and are not shown on the plot). The correlations are rather significant: one observes 14 coincidences within 3° at 3.5 expected for random distribution. This suggests that new coincidences appear as compared to the case of EGRET sources associated with known BL Lacs. The candidate UHECR sources which follow from this analysis are listed in Table 2. Only 4 out of 12 objects (they are marked by star in the third column) are also present in Table 1, while the remaining 8 are new. The most straightforward interpretation of this fact is that there are unknown BL Lacs behind some of these 8 unidentified EGRET sources.

To summarize, there exists a significant correlation of arrival directions of UHECR with γ-ray loud BL Lacs (BL Lacs which may be associated with the EGRET sources). This confirms the conjecture that strong gamma ray emission is a characteristic feature of those BL Lacs which are the sources of UHECR. The strong correlation of UHECR with high-latitude unidentified EGRET sources suggests that some of these sources are in fact BL Lac objects.

The results presented here suggest that the sources of UHECR are high-frequency peaked BL Lacs located at the opposite to FSRQ end of the "unified blazar sequence" (Ghisellini et. al. 1998). This does not contradict to the conclusions of Sigl et. al. (2001) who found no correlations between UHECR and *identified* EGRET blazars. Indeed, most of the latter are high-polarization blazars, and not low-polarization high-frequency peaked BL Lacs which, according to our study, are most probable sources of UHECR.

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AAS LaTeX macros v5.0.

3EG J (1)	E ID (2)	 (3)	l (4)	b (5)	E (6)	Q (7)
0245+1758			157.6	-37.11	3.2	+1
0329+2149			165.0	-27.88	4.8	+1
0429+0337			191.4	-29.08	6.19	+1 or 0
0433+2908	A	*	170.5	-12.6	5.47; 4.89	+1 or 0
1227+4302			138.6	73.33	4.3	+1
1308+8744			122.7	29.38	3	+1
1337+5029			105.4	65.04	5.68	+1
1424+3734		*	66.82	67.76	4.97	+1 or 0
1733+6017		*	89.12	32.94	2.5	+1
1824+3441			62.49	20.14	9.79	+1 or 0
1850+5903		*	88.92	23.18	5.8; 2.8	+1
1835+5918			88.74	25.07		+1

Table 2: List of EGRET sources (previously unidentified or with unknown redshift) and UHECR which correlate with each other.

Notes: Star in the column (3) marks object already present in Table 1. Other columns are the same as in Table 1.

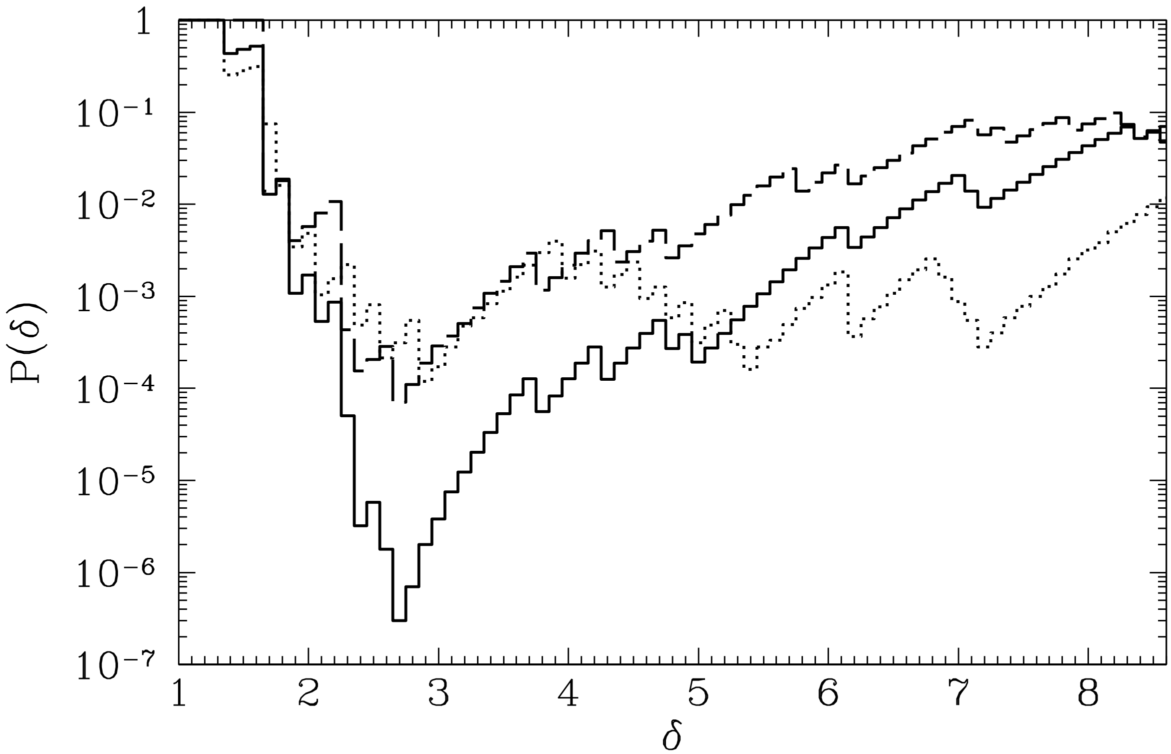

Fig. 1.— Significance of correlations between 14 γ-ray loud BL Lacs and UHECR as a function of the angular scale δ. Dotted, dashed and solid lines represent cases $Q = 0$, $Q = +1$ and $Q = 0, +1$, respectively.

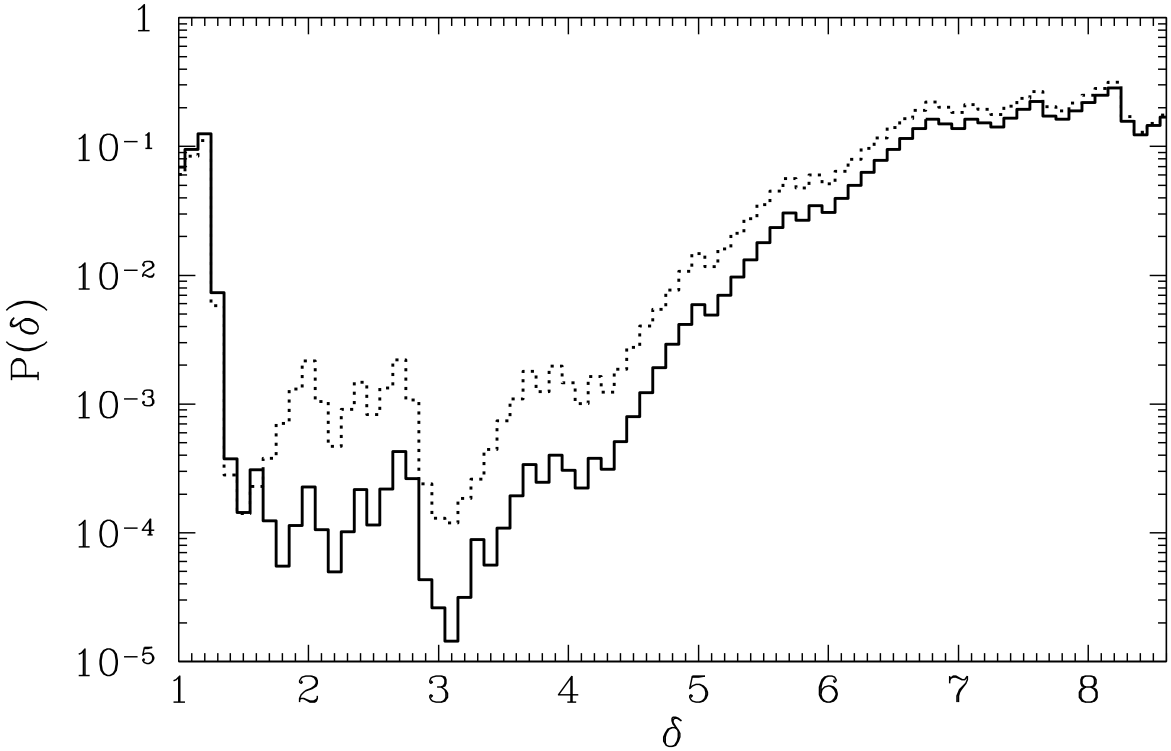

Fig. 2.— Significance of correlations between unidentified EGRET sources and UHECR (dotted line), and between sources with unknown redshift and UHECR (solid line), as a function of the angular scale δ.