EVIDENCE FOR A CONNECTION BETWEEN THE γ-RAY AND THE HIGHEST ENERGY COSMIC-RAY EMISSIONS BY BL LACERTAE OBJECTS

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ABSTRACT

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

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

The highest energy cosmic rays with energies in excess of 10^{19} eV (ultra–high-energy cosmic rays [UHECRs]), observed by the Akena Giant Air Shower Array (AGASA; Takeda et al. 1999) and Yakutsk (Afanasiev et al. 1996) experiments, show a significant number of clusters at angles on 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 a probability of less than 10^{-5} to occur as a result of a statistical fluctuation. This suggests that (1) there exist compact sources of UHECRs and (2) the already existing data may contain information sufficient to identify 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 are relevant candidates. Significant correlations were found with the subset of most powerful confirmed BL Lac objects. After assigning penalties for subset selection and bin size adjustment, the probability of such correlation to occur by chance in a random distribution is on the order of 10^{-4}. BL Lac objects comprise a subclass of blazars 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 the acceleration of particles to highest energies. For this reason, BL Lac objects may be particularly promising candidates for UHECR sources.

It follows from both the statistical arguments (Dubovsky et al. 2000) and correlation analysis (Tinyakov & Tkachev 2001b, 2001c) that only a small fraction of existing BL Lac objects should be capable of producing highest energy cosmic rays. For understanding the nature of the sources and the mechanism of UHECR emission, the key question is which physical characteristics single out the actual emitters among all BL Lac objects? In this Letter we propose that the strong γ-ray emission is the feature that 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 in the intergalactic space 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 1997). In models involving neutrinos via the Z-burst mechanism (Fargion et al. 1999, 2001; Weiler 1999) and those based on very high energy photons (Kalashev et al. 2001; Neronov et al. 2002), the astrophysical accelerator must be very powerful to provide sufficient flux of primary ultra–high-energy particles. In these models, one may expect a strong electromagnetic radiation from the source and substantial contribution into EGRET flux. Note that the *extragalactic* cascade may get isotropized by random magnetic fields when approaching the low-energy end; this may cause smearing of point sources and result in contributions into γ-ray background. In any case, these arguments suggest that γ-ray emission may be an important distinctive feature of UHECR sources.[4]

In order to test this hypothesis we first select those BL Lac objects that can be associated with γ-ray sources and then study their correlations with UHECR. The most complete list of the γ-ray sources can be found in the third EGRET catalog (Hartman et al. 1999) containing 271 objects. Of these objects, 67 are identified with active galactic nuclei (AGNs), five with pulsars, one with a solar flare, one with the LMC, and 27 are tentatively identified with AGNs. The remaining 170 objects are unidentified.

In this Letter 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: we take the full set of confirmed BL Lac objects from the Veron2001 catalog (Véron-Cetty & Véron 2001) consisting of 350 objects, and we select a subsample of those that may be associated with an EGRET γ-ray source. The selection procedure is as follows: Point sources in the EGRET catalog are defined as a local excess of a signal over the 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 the sources. However, the 95% contours are often noncircular. Additional systematic errors in position determination may be present in the case of a bright nearby source (such cases are

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TABLE 1
BL Lac Objects Associated with EGRET Sources and UHECRs
that Contribute to Correlations

3EG J (1)	EGRET ID (2)	Possible BL Lac Object (3)	l (4)	b (5)	z (6)	E (7)	Q (8)
0433+2908	AGN	2EG J0432+2910*	170.5	−12.6	...	5.47	0, ±1
						4.89	0, +1
0808+5114	Possible AGN	1ES 0806+524*	166.2	32.91	0.138	3.4	0
						2.8	0
						2.5	0
0812−0646	Possible AGN	1WGA J0816.0−0736	229.8	14.96	0.04	...	
1009+4855	Possible AGN	GB 1011+496	165.5	52.71	0.2	...	
1052+5718	Possible AGN	RGB J1058+564*	149.6	54.42	0.144	7.76	0, −1
						5.35	0, −1
						5.50	−1
1222+2841	AGN	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, +1
1605+1553	AGN	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
						6.93	−1
1850+5903		RGB J1841+591	88.68	24.29	0.53	5.8	+1
						2.8	+1
1959+6342		1ES 1959+650	98.0	17.67	0.047	5.5	+1
2352+3752	Possible AGN	TEX 2348+360	109.5	−24.91	0.317	...	

Note.—Col. (1): EGRET name; col. (2): EGRET identification; the five objects marked with an asterisk are the cases when suggested identification agrees with the SIMBAD database; col. (3): suggested BL Lac counterpart; Cols. (4) and (5): Galactic coordinates of the BL Lac counterpart; col. (6): redshift of the BL Lac counterpart as given by Véron-Cetty & Véron 2001; col. (7): energies of correlating cosmic rays in units of 10^{19} eV; col. (8): UHECR charge assignments under which the correlation occurs.

marked as "confused" in the catalog). As a result, many well-identified sources (e.g., the Vela pulsar that 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 cases of ambiguity the nearest neighbor is taken.

According to this procedure, 14 BL Lac objects from the Veron2001 catalog are associated with EGRET sources. They are listed in Table 1. Of these 14 objects, eight already have identifications in the EGRET catalog, while six are newly proposed identifications. Out of eight previously identified objects, five have the same identifications in the SIMBAD database as is suggested by our procedure (objects marked by asterisks in Table 1). Interestingly, in those three cases when our procedure suggests identification different from the existing one, the latter has a question mark in the SIMBAD database, while in five 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 Lac objects.

Since the EGRET 95% contours are large enough to contain several astrophysical objects, the identifications depend on the assumptions about candidate sources. Most 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-ray and moderate radio sources (*ROSAT*–Green Bank catalog) were considered. It revealed several new identifications, a large fraction of them being BL Lac objects.

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 Letter. It is important to note, however, that possible misidentifications in Table 1 do not compromise our main result, strong correlation of the selected subsample with UHECRs. Like any random factor, such misidentifications can only diminish the correlations.

Let us now turn to correlations between the set of 14 (potentially) γ-ray–loud BL Lac objects of Table 1 and UHECRs. In the part concerning UHECRs, we follow the approach of Tinyakov & Tkachev (2001b) and use the set of cosmic rays with the largest autocorrelations. This set consists of 39 AGASA events with energies $E > 4.8 \times 10^{19}$ eV and 26 Yakutsk events with energies $E > 2.4 \times 10^{19}$ eV (Tinyakov & Tkachev 2001a).

The numerical algorithm used in this Letter is identical to that of Tinyakov & Tkachev (2001a, 2001b, 2001c). We characterize the significance of correlations between UHECRs 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 source/cosmic-ray pairs separated by the angle ≤δ 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 number of clusters added in each mock set mimics the real data, while cluster positions are random. For each mock set, the number of source/cosmic-ray pairs is then counted in the same way as for the real data, giving the mock count $N_m(\delta)$. At a 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 correlation analysis, we take into account possible effects of the Galactic magnetic field (GMF) on propagation of UHECRs. We use the spiral model of GMF with different

TABLE 2
CORRELATIONS BETWEEN 14 BL LAC OBJECTS AND 65 COSMIC RAYS

	ANTISYMMETRIC FIELD			SYMMETRIC FIELD		
Q	$p(\delta)$	N^a	δ (deg)	$p(\delta)$	N^a	δ (deg)
0	10^{-4}	8	2.9	10^{-4}	8	2.9
+	7×10^{-5}	8	2.7	9×10^{-4}	9	3.7
0, + ...	3×10^{-7}	13	2.7	2×10^{-6}	12	2.6
0, ±	10^{-6}	15	2.8	2×10^{-6}	15	2.9

NOTE.—Summary of correlations between 14 BL Lac objects and 65 cosmic rays for different charge assigments and models of the GMF.
[a] N stands for data count, $N \equiv N_d(\delta)$.

FIG. 1.—Significance of correlations between 14 γ-ray–loud BL Lac objects and UHECRs as a function of the angular scale δ for the $Q = 0, 1$ charge composition. This corresponds to the lowest probability entry in Table 2.

directions of the field in the two spiral arms and consider two cases: symmetric and antisymmetric fields with respect to the galactic disk. The details of the model and corresponding parameters can be found in Tinyakov & Tkachev (2001c) together with further references. We assume that primary particles can have charges of $Q = 0, \pm 1$.

In the case $Q \neq 0$, the positions of cosmic rays are corrected for the deflections in GMF prior to counting the number of pairs with given angular separation. For each cosmic ray there are several possible positions after correction for GMF corresponding to different allowed charges. For a given ray, the minimum angular distance over the set of sources and charges determines the resulting charge assigned to that ray. In all cases, each randomly generated 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 for the charge assignments $Q = 0$, $Q = 1$, $Q = 0, 1$, and $Q = 0, \pm 1$ and for two types of magnetic field (symmetric and antisymmetric) are presented in Table 2. The correlations are rather significant in all cases, being the best in the case of charges $Q = 0, 1$ and antisymmetric field, in agreement with Tinyakov & Tkachev (2001c). In this case, the data count $N_d(2°7) = 13$, while 2 is expected in average for a uniform background. The probability for this to occur by chance is $p(\delta) = 3 \times 10^{-7}$ (5.1 σ). The dependence of $p(\delta)$ on δ in this case is shown in Figure 1.

From the analysis of Table 2 one is tempted to conclude that the case $Q = 0, 1$ (neutral and positively charged particles) is favored. However, present statistics are not enough for such a conclusion, as the following simple argument shows. The data count is subject to fluctuations that may be roughly estimated as $\pm \sqrt{N_d}$ (these fluctuations would be observed if the AGASA and Yakutsk experiments were repeated many times). If the "average" data count were 10, counts from seven to 13 would occur equally often. Corresponding probabilities $p(\delta)$ would range from 10^{-4} to 10^{-7}. Thus, unlike correlations themselves, the *difference* between the cases $Q = 0$, $Q = 0, 1$, and $Q = 0, \pm 1$ can easily be explained by a fluctuation.

Energies and charges of UHECR events that contribute into correlations with γ-ray–loud BL Lac objects are listed in columns (7) and (8) of Table 1 (the antisymmetric magnetic field model is assumed). Multiple charges in column (8) mean that the corresponding event contributes to correlations under different charge assignments.

The comparison between Table 1 of this Letter and Table 1 of Tinyakov & Tkachev (2001b) shows that the same BL Lac objects and cosmic rays contribute to correlations in Tinyakov & Tkachev (2001b) and in the case of $Q = 0$ presented above. In Tinyakov & Tkachev (2001b), the set of brightest BL Lac objects was sel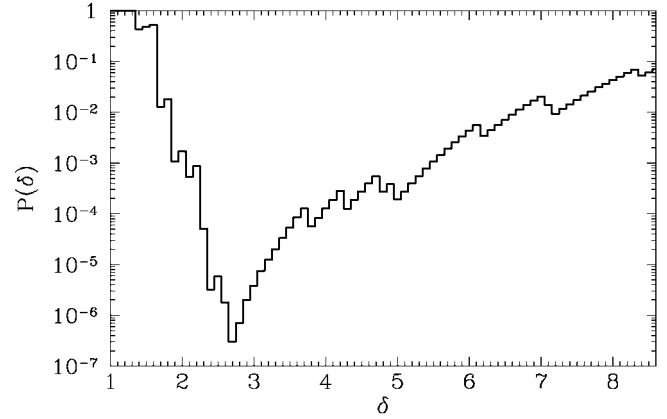ected by imposing cuts on redshift, apparent magnitude, and radio flux. In the resulting subset of 22 BL Lac objects, five candidate sources were identified. It is remarkable that four out of these five candidates, in particular all three that correlate with UHECR multiplets, are among the 14 BL Lac objects that comprise the intersection of BL Lac and EGRET catalogs, γ-ray–loud BL Lac objects. Even more remarkable is that out of 10 remaining BL Lac objects, four correlate with cosmic rays after correction for GMF. Among the remaining six that do not correlate with UHECRs, two 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 Lac objects (eight out of 12) correlate with UHECR. One concludes that the ability to emit γ-rays may be used as the physical criterion that allows to select actual UHECR sources from the set of all BL Lac objects.

BL Lac objects are typically faint objects. Some of the unidentified EGRET sources may be actually BL Lac objects that have not yet been observed at other wavelengths, or have been observed but not identified as BL Lac objects. If this is the case and our conclusion about the connection between γ-ray and UHECR emissions is correct, one may expect correlations between unidentified EGRET sources and UHECRs. To check this, we calculated correlations between UHECRs and unidentified EGRET sources having Galactic latitude $|b| > 10°$ (the cut $|b| > 10°$ is made to increase the fraction of extragalactic sources as, according to Grenier 2000, the total number of such sources is expected to be 30–40 only). This set contains 96 objects. Correlations are best when all particles are assumed to have a charge of $Q = +1$; corresponding significance is $p(\delta) = 10^{-4}$ at $\delta = 3°$. Table 3 summarizes EGRET sources and cosmic rays that contribute to correlations. It is interesting to note that, unlike Table 1, Table 3 seems to favor positively charged particles. We expect that some EGRET sources listed in Table 3 are BL Lac objects that have not yet been observed.

To summarize, there exists a significant correlation of arrival directions of UHECRs with γ-ray–loud BL Lac objects (BL Lac objects that may be associated with the EGRET sources). This confirms the conjecture that strong γ-ray emission is a characteristic feature of those BL Lac objects that are the sources of UHECR. Present data are compatible with charges of primary particles $Q = 0$, $Q = +1$, $Q = 0, +1$, and $Q = 0, \pm 1$, although they favor the latter two cases. It does not seem possible, with the present statistics, to distinguish between

TABLE 3
LIST OF UNIDENTIFIED EGRET SOURCES
CORRELATING WITH COSMIC RAYS

3EG J	l	b	E	Q
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	0, +1
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
1621+8203	115.53	31.77	2.7	+1
1824+3441	62.49	20.14	9.79	0, ±1
1835+5918	88.74	25.07	5.8	+1
			2.8	+1

these cases on the basis of correlation analysis, but it should be possible in the future. This question is of particular interest since specific charge composition is a good signature of most of the existing models. Charge $Q = 0$, ± 1 would speak strongly for neutrino models (Fargion et al. 1999; Weiler 1999). Charge $Q = 1$ would favor protons accelerated in BL Lac objects (note that the energies of most of the $Q = 1$ events in Table 1 would allow them to reach us from super–Greisen-Zatsepin-Kuzmin distances provided extragalactic magnetic fields are small). The cases $Q = 0, 1$ and $Q = 0$ would sug-

gest, in view of the distance to BL Lac objects and presence of neutral particles, the existence of new physics (e.g., exotic neutral particles; Chung et al. 1998; Berezinsky et al. 2002; Gorbunov et al. 2001) or violation of Lorentz invariance (Coleman & Glashow 1999; Dubovsky & Tinyakov 2002).

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

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