Gamma-ray emission as a tracer of UHECR sources

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Abstract

We present evidence in favor of a connection between gamma-ray and UHECR emissions by BL Lacertae objects. We select a subset of gamma-ray–loud BL Lacs by intersecting the EGRET and BL Lac catalogs. The resulting 14 objects are found to correlate strongly with the arrival directions of UHECRs. We also find significant correlations between UHECR and high-latitude unidentified EGRET sources. This suggests that gamma-ray emission can be used as a tracer of UHECR sources.

1. Introduction

There are general reasons to expect the connection between UHECR and γ-ray emissions by astrophysical objects. Both the acceleration of particles in the source and their subsequent propagation in the intergalactic space is necessarily 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 [1]. The energy flux in UHECR necessary to produce repeated events in AGASA detector is of order 1 $\mathrm{eV\,cm^{-2}s^{-1}}$; this is about an order of magnitude smaller than the energy flux of a typical EGRET source. In some models of UHECR (e.g., in models involving neutrinos via the Z-burst mechanism) the astrophysical accelerator must be very powerful to provide sufficient flux of primary ultra–high-energy particles. In these models, one expects electromagnetic radiation from the source to exceed the power in UHECR by several orders of magnitude. This suggests that γ-ray emission may be an important distinctive feature of actual UHECR emitters.

In this talk we test this hypothesis in the framework of the BL Lac model of UHECR, which is strongly supported by the existence of correlations between arrival directions of UHECR and positions of brightest BL Lacs [3]. To this end, we first select those BL Lac objects that can be associated with γ-ray sources and

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then study their correlations with UHECR.

2. Selection of γ-ray loud BL Lacs

The most complete list of the γ-ray sources can be found in the third EGRET catalog [2] which contains 271 object. 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. We do not, however, rely on the existing EGRET identification. Instead, we adopt a purely statistical approach: we take the full set of confirmed BL Lac objects from the catalog [5] consisting of 350 objects, and 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}. 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 multiple candidates the nearest one is taken.

According to this procedure, 14 BL Lac objects from the Veron2001 catalog are associated with EGRET sources. 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. 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 gives us confidence in the selection procedure adopted. It is important to note that possible misidentifications 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.

3. Correlations with UHECR

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 directions of the field in the two spiral arms. We consider two cases: symmetric and antisymmetric field with respect to the galactic plane. The details of the model and corresponding parameters can be found in Refs. [4] together with further references. We assume that primary particles can have charges of $Q = 0, \pm 1$.

In the part concerning UHECRs, we follow the approach of Ref. [3] and use the set of cosmic rays with *largest autocorrelations*. This set consists of 39

Table 1. Correlations between γ-ray loud BL Lacs and cosmic rays for different charge assignments and models of the GMF.

Q	antisymmetric field			symmetric field		
	$p(\delta)$	$N_d(\delta)$	δ	$p(\delta)$	$N_d(\delta)$	δ
0	10^{-4}	8	2.9°	10^{-4}	8	2.9°
+	$7 \cdot 10^{-5}$	8	2.7°	$9 \cdot 10^{-4}$	9	3.7°
0, +	$3 \cdot 10^{-7}$	13	2.7°	$2 \cdot 10^{-6}$	12	2.6°
0, ±	10^{-6}	15	2.8°	$2 \cdot 10^{-6}$	15	2.9°

AGASA events with energies $E > 4.8 \times 10^{19}$ eV and 26 Yakutsk events with energies $E > 2.4 \times 10^{19}$ eV.

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 summarized in Table 1. The correlations are rather significant in all cases, being the best in the case of charges $Q = 0, 1$ and antisymmetric field. Corresponding significance as a function of separation angle is shown in Fig. 1. It should be noted, however, that unlike correlations themselves, the *difference* between different cases is not statistically significant.

It is remarkable is that out of 14 selected BL Lacs, 8 correlate with cosmic rays. 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 (8 out of 12) correlate with UHECR. We conclude that the ability to emit γ-rays may be that physical criterion which distinguishes actual UHECR sources.

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 not been identified as BL Lacs. 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 that have Galactic latitude $|b| > 10°$ (excluding those selected above as γ-ray–loud BL Lacs). This set contains 96 objects. Correlations are best when all particles are assumed to have charge $Q = +1$; corresponding significance is $p(\delta) \simeq 10^{-4}$ at $\delta = 3°$.

4. Conclusions

To summarize, there exists a significant correlation of arrival directions of UHECRs with γ-ray–loud BL Lacs. This confirms the conjecture that strong γ-ray

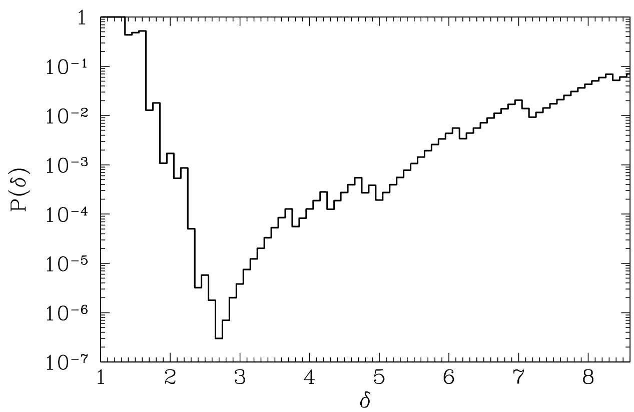

Fig. 1. Significance of correlations between 14 γ-ray loud BL Lac objects and UHECR as a function of the angular scale δ for the $Q = 0, 1$ charge composition and anti-symmetric magnetic field.

emission is a characteristic feature of those BL Lac objects that are the sources of UHECR. Present data are compatible with different charge compositions of primary particles and different GMF models. It does not seem possible, with the present statistics, to distinguish between corresponding cases on the basis of correlation analysis, but it should be possible in the future. This question is of particular interest since charge composition is a good discriminator between the existing UHECR models. Charge $Q = 0, \pm 1$ would speak strongly for neutrino models. Charge $Q = 1$ would favor protons (note that energies of most of the $Q = 1$ events in Table 1 would allow them to reach us from super-GZK distances provided extragalactic magnetic fields are small). The cases $Q = 0, 1$ and $Q = 0$ would signal, in view of the distance to BL Lac objects and presence of neutral particles, the existence of new physics.

Bibliography

1. Berezinsky, V. S., Bulanov S. V., Dogiel, V. A., Ginzburg, V. L., & Ptuskin, V. S. 1990, Astrophysics of Cosmic Rays (Amsterdam: Elsevier); Coppi, P. S. & Aharonian, F. A. 1996, Astrophys. J., L9, 487
2. Hartman, R. C. et al. 1999, ApJS, 123, 79
3. Tinyakov P.G. and Tkachev I.I. 2001, JETP Lett. 74, 445
4. Tinyakov P. G., Tkachev, I. I. 2002, Astropart. Phys. 18, 165
5. Véron-Cetty, M.-P., & Véron, P. 2001, A&A, 374, 92