Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 4 (HE part 1), pages 303–306

30TH INTERNATIONAL COSMIC RAY CONFERENCE

A search for clusters in arrival directions of UHECRs observed by the Yakutsk array

A. A. IVANOV
Yu. G. Shafer Institute for Cosmophysical Research and Aeronomy, 677980, Yakutsk, Russia
ivanov@ikfia.ysn.ru

Abstract: Recent claims of autocorrelations in the data of giant extensive air shower (EAS) arrays and presumable correlations between BL Lacertae and ultra-high energy cosmic rays (UHECRs) incite to sift the Yakutsk array data. Present analysis is based on data recorded between 1974 and 2004, with a total of 19407 showers selected with energies from 10^{18} to 10^{20} eV, zenith angles below 50^0 and axes within array area. An aim is to check whether there is an appreciable flux of neutral particles from BL Lacertae.

Introduction

A direct way to find the hypothesized sources of cosmic rays (CRs) in Ultra-High Energy (UHE) domain ($E > 10^{19}$ eV where their trajectories are not bent noticeably if the particles are charged) is the correlation search for CR arrival directions with the celestial objects surmised. A good deal of effort has been undertaken already in this way. The most promising as yet is the result concerning BL Lacertae, a subclass of blazars, which are active galaxies in which the jet axis points almost directly along the line of sight. In the series of papers [1, 2, 3] the selection criteria were applied to assemble catalogs that show a maximum correlation with arrival directions of cosmic rays above some energy. As a result, UHECRs observed by AGASA, HiRes and Yakutsk experiments were found to have significant correlations with a subset of the most powerful confirmed BL Lac objects. After assigning penalties for subset selection and bin adjustment, the probability of such a correlation to occur by chance in a random distribution was ascertained as 10^{-4}.

Recently, the HiRes collaboration explored the extension of the correlation analysis to EAS events of all energies detected, and the rest of the confirmed BL Lacs (labeled 'HP') in the Veron 10th Catalog [4]. In each case, correlations at the significance level of ~ 0.005 were found [5]. They declared that while statistically independent from the previous result, these are not strictly tests of that claim. However, the combination offers well-defined hypotheses which can be tested with new data.

In this paper an attempt is made to extend a set of EAS events under correlation analysis to lower energies detected with the Yakutsk array, using a parameter connected with the shower maximum position in the atmosphere, X_{max}. The reason is that correlations on the scale of the detector angular resolution 'would suggest neutral cosmic ray primaries for these events, or at least that the primaries were neutral during significant portions of their journey through galactic and extragalactic magnetic fields' [5]. It is assumed that a fraction of neutral cosmic rays from BL Lacs should result in the EAS maximum depth different from that of the main set. The main aim of the paper is to check whether the shower parameter chosen is actually different in two sets.

Slope of the lateral distribution function of charged particles in EAS

It was shown earlier that a slope of lateral distribution function (LDF) of both Cherenkov light and charged particles on the ground can be used as an indicator of EAS maximum position in the atmosphere [6]. An air shower cascading higher in the atmosphere ('old' shower) has broad and flat

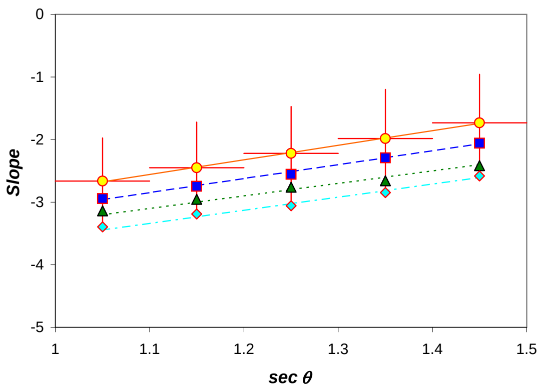

Figure 1: Average slope of lateral distribution function of charged particles as a function of zenith angle and energy. The data are sampled in five $\sec\theta$ intervals shown by horizontal bars; energy bins (in EeV) are: $(1, 1.78)$ - circles; $(1.78, 3.16)$ - squares; $(3.16, 5.62)$ - triangles; $(5.62, \infty)$ - rhombuses; RMS slope errors in bins are shown by vertical bars; approximation lines have $d\eta/d\sec\theta = 2.15 \pm 0.15$.

lateral distribution of secondary particles on the ground while 'young' one has steep LDF.

In this work, the LDF slope of charged particles detected with scintillators of the Yakutsk array is used to distinguish young and old showers in the given energy and zenith angle intervals. Cherenkov light data are not used because of small sample size of showers having this kind of signal detected.

The data set used to analyze the slope parameter consists of events collected during a period 1974 to 2004, with a total of 19407 showers selected with energies from 10^{18} (=1 EeV) to 10^{20} eV, zenith angles $\theta < 50^0$ and axes within array area. Inclined events beyond 50^0 are rejected because of substantial fraction of muonic component in the distribution of charged particles measured. In order to estimate the LDF slope, η, of each shower in a set, additional selection criteria were applied: i) at least 4 stations in the core distance interval $r \in (200, 1000)$ m should have particle density above threshold; ii) the slope calculated using the least square method should be in the interval $\eta \in (-5, 0)$.

Resultant slopes are shown in Figure 1. There is an explicit dependence of LDF slope on energy and zenith angle. It is in agreement with intuitive expectations - an inclined shower should be older than vertical one due to the path length in the atmosphere rising with zenith angle; the shower maximum is shifting down with rising energy, this leads to the lateral distribution steepening, as is seen in Figure. Furthermore, there are arguments in favour of linear (!) relation of LDF slope to X_{max} based on the electromagnetic component behaviour in the atmosphere (as a function of slant depth) independent of zenith angle; discussion is exceeding the bounds of this paper.

Except for a detail concerning average $d\eta/d\sec\theta$. A linear correlation coefficient between the distance to shower maximum ($D_{max} = X_L \sec\theta - X_{max}$, where $X_L = 1020$ g/cm^2 is the observation level of the Yakutsk array) and LDF slope can be derived using the zenith angle dependence of the slope measured. In each energy interval we have $d\eta/d\sec\theta = 2.15 \pm 0.15$. Zenith angle dependence of the distance in inclined showers initiated by protons is given by $dD_{max}/d\eta = X_L d\sec\theta/d\eta$. Applying it to the vertical showers from different primaries we have $-dX_{max}/d\eta = 474 \pm 36$ g/cm^2.

Wilcoxon rank sum criterion

This is one of the far-famed nonparametric significance tests in statistics, known also as Mann-Whitney U test [7]. It is useful for deciding whether the two independent samples of observations belong to the same original distribution. The null hypothesis is that the two samples are drawn from a single population. An advantage of the test is that no assumption is imposed on the distribution of the parameter used.

With the intention to apply a Wilcoxon test to the samples of air showers correlated/uncorrelated in arrival directions with BL Lacs, we have used the rank sum of LDF slopes in two series of events. An idea is that these series can differ in primary particles EAS originate from, because hypothesized UHECRs from BL Lacs are believed to be neutral in order to avoid a dispersion in (inter)galactic magnetic fields, in contrast to the main population thought to be primarily protons. Different primary particles mean different X_{max} of the showers and different slopes of charged particles' LDF on the

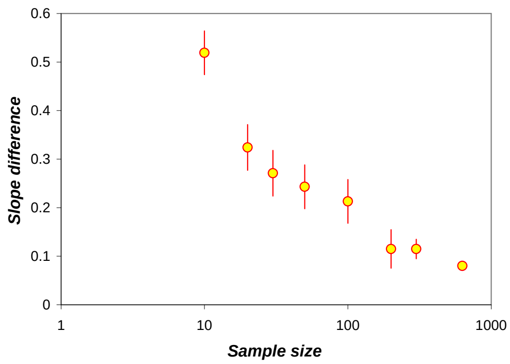

Figure 2: Resolving power of Wilcoxon test. Minimal difference in average LDF slope of two EAS samples with fixed zenith angles and primary energies.

ground which can be tested out if the sample size is sufficient.

In order to reveal the reliability bounds of the Wilcoxon test in our particular case, we have applied the procedure to a pair of samples of EAS events selected in the narrow zenith angle and primary energy intervals ($\Delta\theta = 1^0; \Delta E_0 = 1$ EeV). A rank sum of LDF slopes in $2 \times N$ shower set is then used to distinguish samples on the confidence level 0.01. Varying a distance in zenith angle/primary energy between samples we can set a lower limit to the average slope difference resolvable by the Wilcoxon test. In Figure 2 this limit is shown as a function of the sample size. Experimental errors in charged particle densities measured by scintillators result in uncertainties of slope differences resolved (shown by vertical bars).

LDF slope and BL Lacs

The same data set of the Yakutsk array is used in this section which was used previously to analyze the LDF slope. A method used to select EAS events subset under consideration is based on angular correlation and is following suggestions given in [1]. Namely, the angular distance is calculated between each EAS arrival direction and the position of BL Lac objects on the celestial sphere. Those showers having the distance below 2.5^0 are marked 'On' the sources and are accumulated in the subset A. A bin size $\delta = 2.5^0$ has been shown to provide a minimum of the chance probability of angular correlations between BL Lacs and UHECRs observed to be occurred in the isotropic distribution, using the combined data set of AGASA (39 events, $E > 48$ EeV) and the Yakutsk (26 events, $E > 24$ EeV) arrays [1]. At the same time, it is close to the angular uncertainty in arrival direction of EAS events detected with the Yakutsk array.

We need another set of data in the same energy/zenith angle bins in order to compare LDF slopes of showers. This has been done as follows. For each EAS event in the 2.5^0 vicinity of BL Lacs a counterpart event is found closest in zenith angle and energy which is not marked 'On'. Marking it 'Off' (subset B) we have collected two equal subsets of EAS data - correlated in arrival directions with BL Lacs and the background data - congruous to the circumstances of zenith angle and energy.

Three samples are assumed as possible sources of UHECRs from the 10th Veron Catalog to select EAS arrival directions correlated with BL Lacs:

- *Sample BL:* described in [2], consists of 157 objects with optical magnitude $\mathrm{m} < 18$ which are classified as 'BL' in the Catalog.
- *Sample HP:* other set of 47 confirmed BL Lacs, $\mathrm{m} < 18$, classified as 'HP' (high polarization). This set has been analyzed by the HiRes group [5]; a correlation at the significance level of $\sim 0.5\%$ was found between EAS events with energies above 10^{19} eV and 'HP' objects.
- *Sample G:* described in [3], contains 14 potentially γ-ray-loud BL Lacs which are selected by intersecting 10th Veron and the Third EGRET Catalogs [8].

Having two subsets (sizes are N) of EAS events we can apply Wilcoxon rank sum test in order to decide: is there an appreciable difference in LDF slope of the showers in subsets A/B or these samples are drawn from the same distribution (the null hypothesis)? To do so, we have to count up the number of inversions in subsets of slopes A and B. An inversion is the case when the slope in B is smaller than in A (count is a half for any that are equal). The total of these counts is statistic U. Consulting with statistical tables about the deviation of U from expected value $N^2/2$, we can

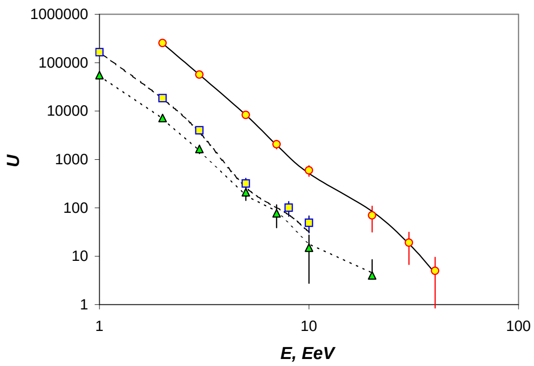

Figure 3: The number of inversions (U) in a pair of LDF slope samples ('On/Off' events). Three samples of BL Lacertae drawn from Veron quasars and active galactic nuclei catalog are used: 'BL' objects (circles); 'HP' objects (squares); γ-ray-loud BL Lacs (triangles). Expected numbers in the case of two samples extracted from the same original distribution are shown by curves. Vertical bars are standard errors under the null hypothesis.

Table 1: Upper limit to the difference between LDF slopes (Ł$_{\Delta\eta}$) and shower maxima (Ł$_{\Delta X_{max}}$) in CR ($E > E_{thr}$) beam from BL Lacs and the background EAS events.

E_{thr}, EeV	N	Ł$_{\Delta\eta}$	Ł$_{\Delta X_{max}}$, g/cm^2
3	336	0.11 ± 0.02	52 ± 4
5	129	0.18 ± 0.05	85 ± 8
10	32	0.27 ± 0.05	128 ± 12
20	13	0.45 ± 0.05	213 ± 19

accept or reject the null hypothesis on the significance level specified.

The results of testing applied to samples *BL*, *HP* and *G* are shown in Figure 3. Subsets A and B are drawn from EAS data set with varying lower energy threshold in the interval 1 to 40 EeV for each source sample. No difference is found in LDF slopes between 'On' and 'Off' subsets on the significance level 0.01 in the whole energy range. Only in the sample *HP* there is a deviation from the expected number of inversions around 10 EeV, but it is insignificant. Another test was applied with 'On' CRs angular distance to BL Lacs halved (1.25^0). There is no appreciable difference in A/B slopes in this case, too.

Using the number of showers in a subset A falling into the 2.5^0 vicinity of BL Lacs (sample *BL*, to be definite), and the lower limit of the difference in LDF slope resolvable by the Wilcoxon test for a given sample size N, we can set now an upper limit to the average slope difference as a function of the energy threshold in the CR beam from BL Lacs (Table 1).

The upper limit is also presented (the last column of Table 1) for the difference in the maximum depth of EAS subsets A and B, which is an immediate consequence of the linear correlation between X_{max} and the slope given above.

Conclusion

No difference is found in the LDF slope parameter of the two subsets of EAS events with different threshold energy correlated/uncorrelated with BL Lacs from 10th Veron Catalog. Upper limits are derived to the LDF slope and X_{max} differences of showers as a function of the sample size.

Acknowledgements

This work is partially supported by RFBR (grant #06-02-16973) and MSE (grant #7514.2006.2).

References

[1] P. G. Tinyakov, I. I. Tkachev, JETP Lett. **74**, 1 (2001).

[2] P. G. Tinyakov and I. I. Tkachev, Astropart. Phys. **18**, 165 (2002).

[3] D. S. Gorbunov et al., Astrophys. J. **577**, L93 (2002).

[4] M.-P. Véron-Cetty and P. Véron, Astron.&Astroph. **374**, 92 (2001).

[5] R. U. Abbasi et al., Astrophys. J. **636**, 680 (2006).

[6] M. N. Dyakonov et al., Proc. 19th ICRC, La Jolla (1985) **2**, p.182.

[7] M. Hollander and D. A. Wolfe, Nonparametric Statistical Methods, Wiley (1999).

[8] R. C. Hartman et al., Astrophys. J. Suppl. **123**, 79 (1999).