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Search for correlation of UHECRs and BL Lacs in Pierre Auger Observatory data

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Abstract: Several analyses of the data collected by other experiments have found an excess of cosmic rays in correlation with subclasses of BL Lacs. Data from the Pierre Auger Observatory do not support previously reported excesses. The number of events correlated with BL Lac positions is compatible with that expected for an isotropic flux.

Introduction

Anisotropies in the arrival directions of UHECRs are likely to provide significant clues to their origin and nature. One potential type of sources of UHECRs are BL Lacertae objects, which are a subclass of blazars, active galaxies with beamed emission from a relativistic jet which is aligned roughly toward our line of sight. A correlation larger than that expected on average for an isotropic flux was found [1] between a subset of BL Lac positions and arrival directions of UHECRs recorded by the Akeno Giant Air Shower Array (AGASA) with energies above 48 EeV and by the Yakutsk experiment with energies above 24 EeV (1 EeV $= 10^{18}$ eV). This correlation, as well as others reported in [2, 3] between BL Lacs and UHECRs recorded by the AGASA and Yakutsk experiments, were not supported by the data collected by the High Resolution Fly's Eye (HiRes) air fluorescence detector [4]. However, HiRes registered an excess of correlations with a subset of BL Lacs on a scale consistent with its angular resolution, with maximum significance for events with energies above 10 EeV [4, 5]. This excess occurs in an energy range and angular scale different from previously reported correlations. An assessment of its statistical significance requires the analysis of independent data.

We use data recorded by the Surface Detector of the Pierre Auger Observatory between 1 January 2004 and 15 March 2007 to search for cross-correlations with BL Lacs, particularly to test previous potential signals. The number of events with energies above 10 EeV in the present analysis is more than 6 times larger than used in preceding cross-correlation searches. Our data do not support previously reported excesses.

Data set and methods

Hybrid operation of the Pierre Auger Observatory allows precision energy calibration of the large number of events recorded by its Surface Detector (SD), as well as several consistency checks to be performed. The energy and angular reconstruction accuracy of the SD are described in detail elsewhere [6]. The quality trigger implemented in the present analysis requires at least five surface stations around that with the highest signal to be active when the event was recorded, and that the reconstructed shower core be inside a triangle of active stations [7]. We use events recorded by the SD with energies above 3 EeV and zenith angles smaller than 60°. There are 14143 events in the data set, of which 1672 have energies above 10 EeV. This set does not include a small fraction of events with energies above 10 EeV that triggered less than 6 surface stations, nor events with

energies below 10 EeV that triggered less than 4 stations. The angular resolution of the SD array is defined as the angular aperture around an arrival direction of CRs within which 68% of the showers are reconstructed. It is 0.9° for events with energies above 10 EeV and 6 or more stations triggered, and 1.2° for events with energies above 3 EeV and 4 or more stations triggered.

The acceptance area of the SD is saturated for events with energies above 3 EeV, and is only limited by geometric effects, which produces a simple analytic dependence upon declination. The small modulation of the exposure in right ascension originated by the present continuous array growth as well as from detectors dead periods can be estimated from the number of active stations as a function of time. It can be ignored, since it has negligible effects upon the analysis performed in this work. It is then straightforward to evaluate the probability p that an individual event from an isotropic flux has its arrival direction less than a given angular distance away from at least one member of a collection of candidate point sources. The probability that k or more out of a total of N events from an isotropic flux are correlated by chance is given by the cumulative binomial distribution $P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}$. The significance of P is controversial [8] if the parameters of the search, such as the angular scale, energy threshold and the collection of candidate sources, are not fixed a priori. An estimate of the chance probability for a particular correlation search is given by the fraction of simulated isotropic sets that have a smaller or equal value of P than the data anywhere in the parameter space, after a scan in the angular scale and energy threshold [9].

Test of previous correlation signals

We test previously reported correlations between UHECRs and subsets of BL Lacs. Note that we test the physical hypothesis of correlation with a particular class of objects at a given angular scale and above a given energy threshold, but the collections of candidate sources are not identical to those in the original reports, because the sky observed by the southern Pierre Auger Observatory is different, and has only a partial overlap.

- **Test A:** 22 BL Lacs from the $9^{\rm th}$ edition of the catalog of quasars and active nuclei [10], with optical magnitude $m < 18$, redshift $z > 0.1$ or unknown, and 6 cm radio flux $F_6 > 0.17$ Jy. 8 of these BL Lacs are in the field of view (f.o.v.) of the Pierre Auger Observatory with zenith angles smaller than 60°.
- **Test B:** 157 BL Lacs (76 in the f.o.v.) from the $10^{\rm th}$ edition of [10] with $m < 18$.
- **Test C:** 14 BL Lacs (3 in the f.o.v.) selected on the basis of possible association with γ-ray sources [3].
- **Test D:** 204 confirmed BL Lacs (106 in the f.o.v.) from the $10^{\rm th}$ edition of [10] with $m < 18$. Subclasses: a) 157 BL, b) 47 HP.

Confirmed BL Lacs are classified by spectral properties as BL or HP (high optical polarization) in [10]. The objects tested in cases A, B and C are those classified as BL only.

Table 1 summarizes the results of the tests. It lists the case considered, the reference for the original report, the lower energy threshold, the number of events with energy above that threshold, the angular size of the search, the number of events observed to correlate within that angular size, the mean number of correlations expected by chance for an isotropic flux, and the chance probability P.

Our data do not support any of the previously reported correlation excesses. There is no significant correlation either, when the tests are performed with the same selection criteria against the BL Lacs in the latest ($12^{\rm th}$) edition of the catalog of quasars and active nuclei [10]. Nor is there any significant excess if the lower energy thresholds are changed $\pm 20\%$ from those of preceding analyses, to account for potential differences in energy calibration between different experiments.

The determination of the statistical significance with which our measurements exclude the hypothesis that the signal present in the HiRes data set (case D) is due to correlations with BL Lacs is a delicate issue. The sky observed by the two experiments is not the same. Catalog incompleteness and the possibility of different selection effects in the two fields of view additionally complicate comparisons. The HiRes data set has 271

Test	Ref.	E_{th} (EeV)	Number of events	Angular size	Observed	Expected (isotropic)	Probability
A	[1]	24	267	2.5°	1	1.0	0.63
B	[2]	40	62	2.5°	2	2.5	0.71
C	[3]	24	267	2.9°	1	0.5	0.41
D	[4]				11	12.1	0.66
a)	[4, 5]	10	1672	0.9°	8	8.9	0.67
b)	[4]				3	3.2	0.62

Table 1: Summary of tests of previously reported correlations. See the text above for details.

events with energies above 10 EeV. Its correlation signal is best fit, using a maximum likelihood method [4], with $n_s = 11$ cosmic rays that come from source positions ($n_s = 8$ from objects classified as BL and $n_s = 3$ from objects classified as HP). Our correlation search was performed at the scale of the angular resolution of the SD array (0.9°). We thus expect to reconstruct inside a search window 68% of the showers initiated by CRs with arrival direction coincident with a BL Lac position. There are 106 confirmed BL Lacs with $m < 18$ in the field of view of the Pierre Auger Observatory, and 186 in the HiRes case. The ratio between the number of candidate sources in each field of view, weighted by the respective relative exposure, is approximately 0.4. Assuming that the degree of correlation is comparable in different portions of the sky, the excess correlation in HiRes data suggests the hypothesis that, using the same catalog and selection criteria, the correlation between BL Lac positions and UHECRs arrival directions should be of greater statistical significance in the Pierre Auger Observatory data set. Normalization to the signal in HiRes data suggests an expectation of $11 \times (1672/271) \times 0.68 \times 0.4 \approx 18.5$ events within 0.9° from candidate sources in the Pierre Auger Observatory field of view, in addition to a mean of 12.1 events from an isotropic background. The observation of a total of 11 events is strongly against the correlation hypothesis.

Extended search

We have extended our search for correlations with BL Lac positions to energy ranges and angular separations different than those that gave maximum signals in previous analyses. These extended searches also serve to account for potential differences in energy calibration and angular accuracy between different experiments that could make a possible correlation signal appear in a different range of parameters.

As an illustration, we plot in the left panel of Figure 1 the number of CRs with energies above 10 EeV that are correlated with any of the 204 confirmed BL Lac positions of case D as a function of angular distance. The solid line is the mean number of correlations expected by chance for an isotropic flux. Fluctuations in 95% of simulated isotropic sets are contained within the bars. The right panel is the analogous plot as a function of threshold energy, for angular separations below 0.9°. There is not an excess for the specific energy threshold and angular separation tested in the section above, nor is any significant excess found for neighboring values of those parameters.

We have extended the search for correlations with all the subclasses of BL Lacs in the previous section, selected both from the catalog versions used in preceding searches as well as from its latest ($12^{\rm th}$) edition. We have scanned the lower energy threshold starting from 3 EeV, eliminating the event with lowest energy in each scan step. We have scanned the angular separation starting from 0.9° for energies above 10 EeV and from 1.2° for lower energy thresholds (the decrease in angular resolution does not justify a scan at smaller separations). The angular separation was scanned up to 3°. The search gave no significant correlation excess. The smallest value found for the probability P that the observed correlation in a given scan step happened by chance under isotropic conditions was $P = 0.03$. This value corresponds to the

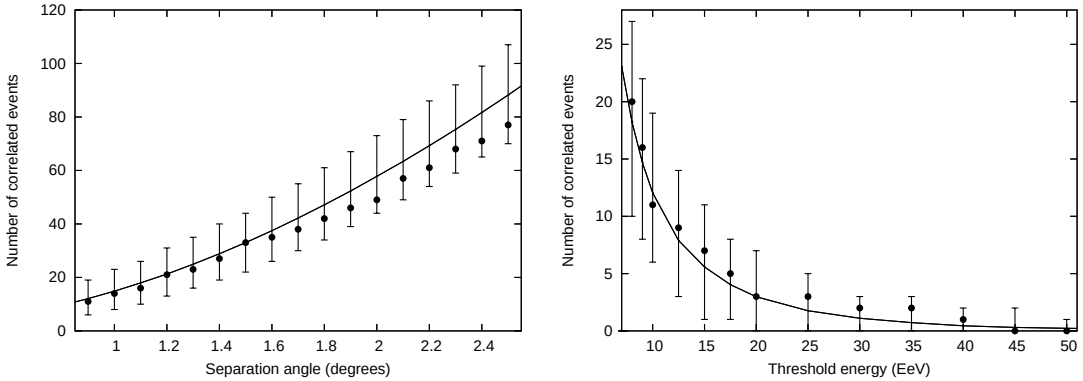

Figure 1: Number of events correlated with confirmed BL Lacs with optical magnitude $m < 18$ from the $10^{\rm th}$ edition of the catalog of quasars and active galactic nuclei [10] (points) and average for an isotropic flux (solid line) along with dispersion in 95% of simulated isotropic sets (bars). Left: as a function of the angular separation (threshold energy fixed at 10 EeV). Right: as a function of threshold energy (angular separations below 0.9°).

observation of 6 CRs among the subset of the 69 events with energy above 38.8 EeV with arrival direction less than 2° away from one of the 204 confirmed BL Lacs of case D (4 from objects classified BL, 2 from objects classified HP), while 2.4 are expected on average for an isotropic flux (1.8 around BL objects, 0.6 around HP BL Lacs). Since 12% of simulated isotropic sets have equal or smaller value of P somewhere in the parameter space after a similar scan, the excess observed is compatible with expected fluctuations under isotropic conditions.

Conclusion

Data from the Pierre Auger Observatory, with 6 times more events with energy above 10 EeV than used in preceding searches, do not support previously reported excesses of correlation between the arrival directions of UHECRs and subclasses of BL Lacs. The number of correlations found is compatible with that expected for an isotropic flux.

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