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Search for Cross-Correlations of Ultra–High-Energy Cosmic Rays With BL Lacertae Objects

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The High Resolution Fly's Eye (HiRes) experiment is a stereo air fluorescence detector for the study of cosmic rays with energies above 5×10^{17} eV. Arrival directions of cosmic rays observed in stereo can be resolved with a typical uncertainty on the order of $0.5°$, making the experiment ideal for small-scale anisotropy studies. Here we present the results of searches for correlation with astronomical sources, in particular the recently observed correlations with objects of the BL Lac subclass of active galaxies.

1. Introduction

One of the most striking astrophysical phenomena today is the existence of cosmic ray particles with energies up to and exceeding 10^{20} eV. It is currently unknown where and how these particles are accelerated to such energies. Among the potential sources which have been considered are BL Lacertae objects. BL Lacs are a subclass of blazars, which are active galaxies in which the jet axis happens to point almost directly along the line of sight. Blazars are established sources of high energy γ-rays above $100\,\mathrm{MeV}$ [1], and several BL Lac objects have been observed at TeV energies with ground-based air Cherenkov telescopes. High energy γ-rays could be by-products of electromagnetic cascades from energy losses associated with the acceleration of ultra–high-energy cosmic rays (UHECR) and their propagation in intergalactic space [2, 3].

Significant correlations between subsets of BL Lac objects and cosmic rays observed by the Akeno Giant Air Shower Array (AGASA) and Yakutsk experiments have been claimed [4, 5, 6]. However, the claims are controversial [7, 8], and in some cases it has been shown that statistically independent data sets do not confirm the correlations [9].

Stereoscopic operation of the High Resolution Fly's Eye (HiRes) air fluorescence detector is providing a large data set of cosmic ray events with unprecedented angular resolution for the study of small-scale anisotropy and source correlations. In this paper, we report on searches for correlations between BL Lac objects and HiRes stereoscopic events observed between 1999 December and 2004 January. The quality cuts applied to this data sample are described in detail in [10, 11].

2. Maximum Likelihood Method

We apply an *unbinned* maximum likelihood method in the search for UHECR correlations with point sources. This approach uses the probability density function for each individual event rather than requiring a fixed bin size. Two important advantages of this method are the ability to accommodate events with different errors, and to give weighted sensitivity to angular separations—avoiding the loss of information that follows from choosing an angular separation cut-off. The method is described in detail in [11].

Briefly, the premise involved in the maximum likelihood analysis is that the data sample of N events consists of n_s source events which came from some source position(s) in the sky, and $N - n_s$ background events. The probability distribution of arrival directions $\mathbf{x}$ for a source event is given by $Q_i(\mathbf{x}, \mathbf{s})$, which depends on the source location $\mathbf{s}$ and the ith event's angular error function. The probability distribution of arrival directions for a background event is given by the detector exposure to the sky, $R(\mathbf{x})$.

Given a set of M source locations, we define the total source probability distribution $Q_i^{tot}(\mathbf{x})$ for the ith event as the sum of the individual source probabilities, each weighted by the detector's exposure to the jth source:

$$Q_i^{tot}(\mathbf{x}) = \sum_{j=1}^{M} Q_i(\mathbf{x}, \mathbf{s}_j) R(\mathbf{s}_j) / \sum_{k=1}^{M} R(\mathbf{s}_k) \quad . \tag{1}$$

We use Q_i^{tot} (rather than Q_i) to define the partial probability and likelihood functions (see [11] for details).

The best estimate for the number n_s of events contributed by the sources can be determined by finding the value of n_s that maximizes the likelihood ratio $\mathcal{R}$:

$$\mathcal{R}(n_s) = \prod_{i=1}^{N} \left\{ \frac{n_s}{N} \left(\frac{Q_i^{tot}(\mathbf{x}_i)}{R(\mathbf{x}_i)} - 1 \right) + 1 \right\} \tag{2}$$

In practice, we maximize $\ln \mathcal{R}$. The maximized value of $\ln \mathcal{R}$ is a measure of the deviation from the null hypothesis ($n_s = 0$). We estimate the significance by performing the same likelihood analysis on simulated data sets and ranking them according to their $\ln \mathcal{R}$ values. We will use $\mathcal{F}$ to denote the fraction of simulated, isotropic event sets which yield a value of $\ln \mathcal{R}$ greater than or equal to that of the data. It is worth emphasizing that n_s denotes the *excess* number of events correlating with source positions, above the background expectation.

For the source probability function Q_i we employ a circular Gaussian of width σ_i corresponding to the angular uncertainty of the ith event, as estimated by the stereo event reconstruction. For the background probability function $R(\mathbf{x})$, we use two methods: for large event samples ($\gtrsim 1000$), we generate a background distribution from a full time-swapping of the data itself: the equatorial coordinates of each event are recalculated using all of the recorded event times, and $R(\mathbf{x})$ is the cumulative map of all of these virtual event locations convolved with a circular Gaussian function for smoothing. For small event samples we rely on a full detector simulation; this is described in more detail in [10].

3. Analysis

The 271 published HiRes events above 10^{19} eV were recently analyzed in [12], and correlations with a sample of 157 BL Lacs from the Veron 10th Catalog [13] were found. The sample consisted of the confirmed BL Lacs classified as "BL" in the catalog with optical magnitude $m < 18$. We verify this analysis by applying the maximum likelihood method to the same data set and source sample, and find $\ln \mathcal{R} = 6.08$ for $n_s = 8.0$; the fraction of Monte Carlo sets with higher $\ln \mathcal{R}$ is $\mathcal{F} = 2 \times 10^{-4}$.

The magnitude cut $m < 18$ was previously identified as enhancing correlations between BL Lacs and the AGASA data [5]. The current HiRes result does not strictly confirm the previous correlations, however, because the energy threshold has been lowered. Using the same energy threshold of 4×10^{19} eV that was used for AGASA, the HiRes data in fact has a deficit of events correlating with this BL Lac sample.

The result nevertheless warrants further study. Because it represents a new claim based on the current HiRes data set, it can only be confirmed with new data. In this paper, we continue analysis with the current HiRes data to explore how variations of the hypothesis affect the result. We report on three results suggesting well-defined, well-motivated hypotheses which can be decisively tested in the future with independent HiRes data.

Event Sample — Low Energy Events: Almost all of the events above 10^{19} eV which contribute to the observed correlation have energies between 10^{19} eV and $10^{19.5}$ eV. At these energies, it is generally assumed that the Galactic magnetic field will deflect a proton primary by many degrees; nuclei will be deflected even more. In spite of this, the correlations are consistent with the $\sim 0.5^\circ$ scale of the detector angular resolution. This would imply that the correlated primary cosmic rays are neutral. Since the chief motivation for restricting the analysis to events above some energy threshold is to minimize the deflections by magnetic fields, this motivation is removed if the primaries are neutral, and an analysis of the entire HiRes stereo data set of 4495 events at all energies is justified.

Applying the analysis to the entire data set and the same sample of BL Lacs, we find correlations at about the same level of significance as originally found for events above 10^{19} eV only: the analysis gives $n_s = 31$, with $\mathcal{F} = 2 \times 10^{-4}$. This of course includes the effect of the correlated events above 10^{19} eV; for the independent sample of 4224 events below 10^{19} eV, we find $n_s = 22$, with $\mathcal{F} = 6 \times 10^{-3}$.

Source Sample — "HP" BL Lacs: The sample of BL Lacs discussed above includes only confirmed BL Lacs which are classified as "BL" in the Veron 10th Catalog. The rest of the confirmed BL Lacs are classified as "HP" (high polarization). It is natural to perform the analysis on these objects; many in fact are among the most luminous BL Lacs. We employ the same cut on optical magnitude $m < 18$ to the "HP" objects, which produces a sample of 47 objects. The result of the maximum likelihood analysis applied to this independent sample of BL Lacs and the HiRes events above 10^{19} eV is $n_s = 3.0$, with $\mathcal{F} = 6 \times 10^{-3}$. We also perform the same analysis on the events below 10^{19} eV. No excess is found.

A summary of the results that are statistically independent is given in Table 1. We have also performed the equivalent analyses on the same classes of BL Lacs with $m \geq 18$: no excess correlation is found in any of these cases. Evidently, that the $m < 18$ cut which was identified in [5] as optimal for AGASA also isolates the BL Lac objects which show excess correlations with HiRes events. Under the BL Lac source hypothesis, of course, it is not unreasonable to expect the closer and more luminous objects to contribute more strongly. However, since the Veron catalog is not a uniform sample of BL Lac objects, the interpretation of this cut may involve a more complicated interplay of selection effects from the underlying surveys which make up the catalog.

Source Sample — TeV Blazars: Among the closest and brightest of the "BL" and "HP" BL Lacs are six which are confirmed sources of TeV γ-rays [14]. All but one are high in the northern sky and well within the field of view of HiRes. We perform the maximum likelihood analysis on this set of six objects using all of the HiRes data, and find $n_s = 5.6$ with $\mathcal{F} = 10^{-3}$. (The maximum likelihood result is unaffected by objects which are outside the field of view, so we do not explicitly remove these objects from any of the analyses.) For just the HiRes events above 10^{19} eV, the result is $n_s = 2.0$, with $\mathcal{F} = 2 \times 10^{-4}$.

4. Results and Discussion

Using an unbinned maximum likelihood method, we have verified the observation in [12] that the set of HiRes stereo events with energies above 10^{19} eV shows correlation with confirmed BL Lacs marked as "BL" in the Veron 10th Catalog. We emphasize that the observed correlation does not confirm a previous claim, because it requires a lower energy threshold. It can only be confirmed with new data.

We have explored the extension of the analysis to 1) HiRes events of all energies, and 2) the rest of the confirmed BL Lacs (labeled "HP") in the Veron 10th Catalog. In each case, correlations at the significance level of $\sim 0.5\%$ are found. While statistically independent from the above result, these are not strictly tests of that claim. However, in combination with that claim they offer well-defined hypotheses which can be tested

Sources (# Obj.)	HiRes Energy Cut [EeV]	Results	
		n_s	$\mathcal{F}$
"BL" (157)	$E > 10$	8.0	2×10^{-4}
	$E < 10$	22.	6×10^{-3}
"HP" (47)	$E > 10$	3.0	6×10^{-3}
	$E < 10$	(0)	0.5

Table 1. Independent HiRes — BL Lac Correlations: Estimated number n_s of source events, and fraction $\mathcal{F}$ of simulated HiRes sets with stronger correlation signal. All samples include the $m < 18$ cut. The results are independent.

Source Sample (# Obj.)	All Energies	$E > 10$ EeV
"BL" (157)	2×10^{-4}	2×10^{-4}
"BL"+"HP" (204)	5×10^{-4}	10^{-5}
TeV Blazars (6)	10^{-3}	2×10^{-4}

Table 2. Combined HiRes — BL Lac Correlations: Fraction $\mathcal{F}$ of simulated HiRes sets with stronger correlation signal. All samples include the $m < 18$ cut. The samples overlap and are *not* independent.

with new data. The combined results are summarized in Table 2. Also shown are the results for HiRes events and the subset of BL Lacs which are confirmed sources of TeV γ-rays.

The HiRes detector will continue observations through the end of 2006 March. By that time the independent sample of data since 2004 January is expected to reach approximately 70 % of the size of the sample analyzed here. This will provide an opportunity to test the correlations in Table 2. We note that while the correlation signals appear stronger for the events above 10^{19} eV, a conservative approach which includes consideration of the entire data set will help to avoid the possibility that a real correlation has been "over-tuned" by an arbitrary threshold and is missed in a future analysis.

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