HiRes Limits on Point-Like Sources of Cosmic Rays with Energy Above $10^{18.5}$ eV

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Abstract: Point-like excesses have been alternately claimed and refuted in the direction of Cygnus X-3, BL-Lacertae objects, and others. We conduct a search for point-like deviations from isotropy in the arrival direction of ultra-high energy cosmic rays in the monocular data set collected by the High-Resolution Fly's Eye. We find no evidence for point-like excesses and place a 90% c.l. upper limit of 0.8 hadronic cosmic rays/km$^2 \times$yr with energies greater than $10^{18.5}$ eV for the northern hemisphere. We place tighter limits as a function of position in the sky.

Introduction

In the search for compact sources of ultra–high energy cosmic rays (UHECR), a variety of strategies have been employed, yielding ambiguous results. Excesses have been alternately claimed and refuted in the vicinity of Cygnus X-3 [7, 13, 12, 6], an x-ray binary within our galaxy, including the report of a possible excess in a point-like source search [8]. The HiRes [1] and Akeno Giant Air-Shower Array (AGASA) [11] experiments disagree on the existence of point-like clusters of particles with energies above 4×10^{19} eV. Recently, possible correlations between UHECR arrival directions and BL-Lacertae (BL Lac) objects have been the subject of study. The earliest reported correlations between events observed by AGASA and Yakutsk [9] with subsets of BL Lacs from the Véron catalog [14] have not been confirmed with HiRes stereo data [2]. However, correlations have been observed between HiRes stereo data above 10 EeV and BL Lac objects, with chance probabilities at the 10^{-3} level [10].

Both galactic and extragalactic magnetic fields are expected to produce large perturbations in the arrival directions of charged particles: a proton with an energy of a few EeV may be deflected by several degrees as it traverses the disk of the Milky Way galaxy. A point-like source at these energies therefore suggests neutral primaries. Neutrons possess a lifetime of 3×10^{12} seconds at 10 EeV and so cannot have originated more than 100 kpc from Earth. Thus any viable source of standard model neutral matter would have to be located within or nearby the Milky Way Galaxy.

In this paper, we conduct a search for point-like (within detector resolution) arrival direction excesses for cosmic ray events above $10^{18.5}$ eV in the northern hemisphere. We use a skymap technique in which we evaluate our sensitivity using Monte Carlo simulated sources and place upper limits on the flux of hadrons from point-like sources, including Cygnus X-3.

HiRes–I Monocular Data

A total of 1,525 airshower events with energies exceeding $10^{18.5}$ eV are included in the present analysis. A residual effect of the profile–constrained fitting technique is orientation–dependent (elliptical) uncertainties in the airshower arrival directions. The shower–detector plane (SDP) for HiRes–I events is well–reconstructed, with uncertainty parameterized as

$$\sigma_{SDP} = 88.2^\circ e^{-\Delta\chi/1.9595} + 0.37^\circ \qquad (1)$$

where $\Delta\chi$ is the angular tracklength of the shower in degrees. The angle of the track within the SDP, Ψ, is less well reconstructed and is parameterized

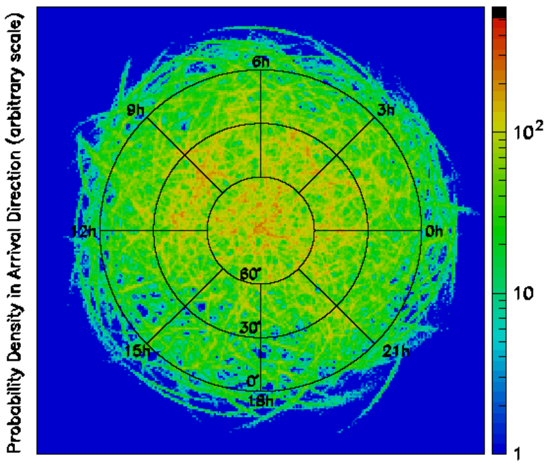

Figure 1: Skymap of arrival directions of events in the the HiRes–I monocular data set, plotted in polar projection, equatorial coordinates. Angular bin size varies across the map, but averages $1^\circ \times 1^\circ$. Each event is represented by 1,000 points randomly thrown according to the elliptical Gaussian error model of Equations 1 and 2.

by

$$\sigma_\Psi = 18.4^\circ e^{-\log_{10}(E)/0.69085} + 4.1^\circ \qquad (2)$$

where the energy E is expressed in EeV (10^{18} eV).

In Figure 1, we plot the skymap formed from the arrival directions of events in the present data set. Each event's "error ellipse" is represented by generating 1,000 points per event, distributed according to the Gaussian error model of Equations 1 and 2.

Monte Carlo Simulation of Background & Point-Like Sources

We use a library of simulated events, generated by the Monte Carlo technique and reconstructed using the profile–constrained reconstruction program to determine the background expectation for isotropically distributed sources as well as to evaluate our sensitivity to point-like behavior in arrival direction. For this library, we assume an isotropic distribution for events possessing the spectrum and composition suggested by the stereo Fly's Eye experiment [4, 5].

In order to understand the significance of the fluctuations in Figure 1, we compare the data on a bin-by-bin basis to 1,000 simulated data sets. Defining N_{DATA} as the bin density of the data, N_{MC} as the bin density of the simulated isotropic data sets, and σ_{MC} as the standard deviation of the Monte Carlo bin density, the variable

$$\xi = \frac{N_{DATA} - \langle N_{MC} \rangle}{\sigma_{MC}} \qquad (3)$$

provides a measure of the fluctuation per bin. However, the distribution of ξ is non-Gaussian. Thus we use the ξ information in neighboring bins to pick out significant fluctuations above background from the skymap. The parameters in this technique are tuned on simulated point-like sources. We also use simulated sources to quantify our sensitivity to point-like excesses and derive flux upper limits.

Simulated source skymaps are created by randomly replacing events in a simulated isotropic data set with N_S events at the chosen position for the source. The energy and error ellipse are taken from the replaced event and the ellipse orientation is randomized. Finally, the central-value coordinates of the simulated source event are randomly shifted according to the error ellipse, simulating the effect of detector resolution.

Extraction of Point-Like Sources

We consider a "search circle" of radius R, where R is expressed as an angle in degrees. Within the search circle, we count the fraction of bins F having an ξ value greater than some threshold ξ_{THR}. $R = 2.5^\circ$ and $\xi_{THR} = 4$ are chosen to optimize the sensitivity to the simulated point-like sources. A cut of $F = 0.33$ is chosen to reduce the false positive probability over the entire sky to an acceptable level of 10%.

In Figure 2, we have plotted for each bin the fraction F of an $N_S = 25$ event source inserted at 5 hours RA, 40° DEC. The simulated source stands out clearly in this figure.

The "hottest" spot on the F map for the HiRes–I monocular data has value $F = 0.15$. 87% of simulated isotropic data sets have a maximum value of $F \geq 0.15$. We conclude that our observation

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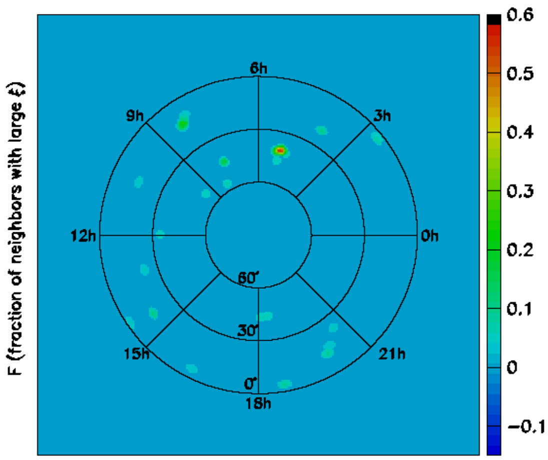

Figure 2: F distribution derived from the ξ map of an $N_S = 25$ event source inserted at 5 hours RA, 40° DEC. F is the fraction of bins within radius $R = 2.5°$ having a ξ value of 4 or greater. The simulated source is visible with an exceptionally large excess fraction F.

is consistent with a fluctuation from an isotropic background.

Sensitivity & Upper Limits

The sensitivity of the experiment is defined as the 90% confidence level flux at which HiRes–I could declare a point-like source. Since this will vary as a function of position on the sky due to different background expectations, we calculate our sensitivity at a set of gridpoints (Table 1). We choose the right ascension values of our gridpoints to correspond approximately to the HiRes "solstices" and "equinoxes", *i.e.* to the RA lines of high, low and midrange event statistics.

To determine our sensitivity to a number of "source" events at a given gridpoint, we generate 400 simulated isotropic datasets with $\langle N_S \rangle$ isotropic events replaced by point-like source events (N_S is Poisson distributed).

We then determine the percentage of trials at each location for which our reconstruction algorithm "finds" a source of size $\langle N_S \rangle$. For sensitivity, we say the algorithm "finds" a source if F fluctuates above our preselected threshold value of $F = 0.33$. The value of $\langle N_S \rangle$ for which signal was declared for 90% or better of the trials was termed $N_{.33}$. The HiRes–I flux sensitivity at each grid point is $N_{.33}$ at that point divided by the local exposure.

We place our 90% confidence level flux upper limits by making use of the fact that F never fluctuated above 0.15 in the HiRes-I data. We determine the value of $N_{.15}$ in the same manner in which we determined $N_{.33}$. Our 90% c.l. flux upper limit at each grid point is $N_{.15}$ at that point divided by the local exposure. The largest flux upper limit is 0.8 hadronic cosmic rays above $10^{18.5}$ eV per km^{2}yr, with all results summarized in Table 1.

Discussion

Cygnus X-3 (RA 20.5 hours, DEC 40.7°) is very near the grid point located at RA 20.5 hours, DEC 45°. We place a 90% c.l. flux upper limit from a point-like source in the vicinity of Cygnus X-3 at 0.5 hadronic cosmic rays above $10^{18.5}$ eV per km^{2}yr.

We have conducted a search for point-like excesses (see also [3]) in the arrival direction of ultra–high energy cosmic rays with energy exceeding $10^{18.5}$ eV in the northern hemisphere. We place an upper limit of 0.8 hadronic cosmic rays/(km^2 yr) (90% c.l.) on the flux from such excesses across the entire sky and place more stringent limits as a function of position. The HiRes–I monocular data is thus consistent with the null hypothesis for point-like sources of hadronic cosmic rays in this energy range.

Acknowledgements

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DEC (deg)	RA ($hours$)	$N_{.33}$	$N_{.15}$	$\langle N_{MC} \rangle$ in 2.5°	Exposure ($km^2 yr$)	Sensitivity ($\text{km}^{-2}\text{yr}^{-1}$)	Upper Limit ($\text{km}^{-2}\text{yr}^{-1}$)
15°	2.5 hrs	23	16	1.3	34.2	.7	.5
	5.5 hrs	24	19	1.4	36.6	.7	.5
	8.5 hrs	22	16	1.2	34.3	.6	.5
	11.5 hrs	20	16	1.1	24.5	.8	.7
	14.5 hrs	18	14	.8	21.9	.8	.6
	17.5 hrs	18	13	.7	16.7	1.1	.8
	20.5 hrs	17	13	.7	21.1	.8	.6
	23.5 hrs	21	16	1.2	26.7	.8	.6
45°	2.5 hrs	26	20	1.8	49.7	.5	.4
	5.5 hrs	29	22	2.0	56.6	.5	.4
	8.5 hrs	25	20	1.7	48.5	.5	.4
	11.5 hrs	24	18	1.5	41.2	.6	.4
	14.5 hrs	21	15	1.2	33.5	.6	.4
	17.5 hrs	21	16	1.0	24.9	.8	.6
	20.5 hrs	21	16	1.2	30.3	.7	.5
	23.5 hrs	24	18	1.5	41.5	.6	.4
75°	5.5 hrs	29	21	2.2	59.8	.5	.4
	11.5 hrs	28	21	2.1	50.5	.6	.4
	17.5 hrs	26	19	1.8	38.6	.7	.5
	23.5 hrs	26	20	2.0	47.2	.6	.4
90°	N/A	31	23	2.5	53.8	.6	.4

Table 1: Locations of gridpoints, threshold signal strengths $N_{.33}$ and $N_{.15}$, mean number of Monte Carlo events, exposures (with uncertainty 5%, primarily from Monte Carlo statistics), detector flux sensitivity, and 90% confidence level flux upper limits, for cosmic rays with energy exceeding $10^{18.5}$ eV.

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