# Anisotropy Studies Of Ultra–High Energy Cosmic Rays Using Monocular Data Collected By The High–Resolution Fly's Eye (HiRes)

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**Abstract**

While the existence of cosmic rays with energies exceeding $10^{18}$ electron-volts has been well established, attempts to correlate these particles with sources have yielded results which are ambiguous at best. Even the highest energy events, whose energies render them largely immune to bending by galactic magnetic fields, have eluded identification with particular sources. We present here the results of new searches for anisotropy within the HiRes monocular dataset, which contains events ranging from $10^{18}$ to over $10^{20}$ eV. Using various skymap analysis techniques, we search for event excesses from *a priori* pointlike sources (Cygnus X-3, M87, and the AGASA "triplet"), extended sources (the galactic and supergalactic planes) and evidence for dipole moments in the full sky survey. We place upper limits on the existence of both pointlike and extended sources within HiRes' Northern Hemisphere field of view.

## 1. Introduction

The High–Resolution Fly's Eye (HiRes) has been collecting data in monocular mode since 1997 and in stereo mode since 1999. Analysis on the monocular data is at an advanced stage, and we present here the results of several anisotropy analyses on the monocular data set.

## 2. Shower Density Sky Maps

The technique of creating shower density sky maps is useful for studying the region of sky around candidate source regions. In producing these maps we incorporate the estimated arrival direction errors for each event, and make use

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of a “shuffling” technique to take account of the non-uniform exposure of the HiRes detector. We make use of the data itself to estimate the significance of any excess or deficit in shower density. The techniques as applied here were developed for use with Fly's Eye data [5], and have also been applied to data from other experiments, (e.g. [2]).

The geometry of events used in this analysis have been determined using a profile-constrained monocular fit [1]. Each event in our data set has a nominal arrival direction, with uncertainties in that direction expressed in terms of an uncertainty in the orientation of the “shower–detector plane” (SDP) normal vector and an uncertainty in the track angle $\psi$ within the plane. For the sky map we represent each event by a gaussian probability function surrounding its nominal direction on the sky. The gaussian has, in general, a different width in each of the orthogonal directions. One dimension is largely determined by the uncertainty in the SDP normal, and the other is determined by the uncertainty in $\psi$. The SDP is usually reconstructed with better precision than the track within the plane, resulting in an elongated two-dimensional gaussian, with its major axis oriented along a line defined by the projection of the SDP onto the sky. Each error gaussian is normalized so that its total “volume” is unity, before being added to the sky map. The sky map thus consists of the sum of all event gaussians, producing a map of shower density that takes into account our estimates of reconstruction uncertainties. We call this the “density map”.

We next compare this map with the expectation based on an isotropic flux of cosmic rays. That expectation must take into account the exposure of HiRes in right ascension and declination. It is determined using the “shuffling” technique [5]. Here, a number of shuffled data sets are derived from the real data set, with each shuffled data set containing the same number of events as the real one. A real arrival time (Julian date) from one event is randomly paired with a local arrival direction (defined by the $\psi$ angle and the SDP normal vector, together with errors in those parameters) from another event in the real data set. This is repeated until a new data set is filled. The new data set has the same arrival time distribution and the same distributions of local arrival directions as the real data set. However, because the pairings have been randomized, all celestial directions have been randomized simulating an isotropic event flux. Many shuffled data sets can be generated. For each of those, an event density map can be generated using 2D gaussian point-spread functions. An average of many such maps provides a convenient and solid representation of the expectation for a flux of isotropic cosmic rays.

Comparing the real density map with the isotropic expectation, we can derive a map showing the fractional excesses and deficits of event densities across the sky. To compute the significance of any excess or deficit we use the shuffled data sets, and use the shuffled data sets and Monte Carlo “artificial sources” to understand detector sensitivity.

## 3. Topical Sources

In addition to the results of shower density sky maps, we present the results of searches for sources of ultra–high energy cosmic rays in the vicinity of a preselected set of topical candidate objects. The technique consists of comparing the density of airshower arrival directions in the vicinity of the candidate objects with the density expected from an isotropic distribution given our detector exposure.

The first source we consider as a possible candidate is Cygnus X–3, which has been identified with a possible excess of cosmic rays in the $\geq 1$ EeV range [4,12].

AGASA recently reported clusters of events including several "Doublets" and one "Triplet" [7]. We will report on the results of a HiRes search for events in the vicinity of the "Triplet" at energies exceeding $4 \times 10^{19}$ eV.

We also consider the galaxy M-87 (Virgo A) [3], due to the recent theoretical interest identifying it as a potential nearby source within the distance constraint imposed by the GZK cutoff [6,13]. For this source, we consider only events with energies exceeding $4 \times 10^{19}$ eV. Of related interest is the extended source in the vicinity of the Supergalactic Plane [8,11].

## 4. Autocorrelation Studies

Autocorrelation makes use of the distribution of space angles between pairs of events. If small-scale anistropies ($\leq 5°$) are present, one will see an enhancement in the autocorrelation function at the smallest space angles.

One can create an autocorrelation function for a given event sample using the following methodology: (1) Take any pair of events. (2) Calculate the cosine of the space angle between the events. (3) Enter that value into a histogram of the cosine of the space angle. (4) Repeat until every possible event pairing has been considered.

In the present case, the monocular profile constraint fit produces large asymmetric errors. However, one can treat each event as a two dimensional, asymmetric gaussian distribution of randomly generated points about its error space. One can then compare the distributions of the pairs of randomly generated points on a one-to-one basis. If one then repeats for all possible pairings, one can create an autocorrelation function that accommodates large, asymmetric errors.

In order to interpret the significance of the autocorrelation function, one can calculate the autocorrelation function of a large number of simulated data sets consisting of monte carlo events with the same aperture as the real data. One can then make a comparison of the autocorrelation function of the real event sample and the autocorrelation *functions* of the simulated data sets to determine the degree to which the real event sample is consistent with being isotropic at small scales.

## 5. Full–Sky Harmonic Analysis

In addition to searching for particular sources, we wish to determine whether or not large–scale patterns exist in cosmic ray arrival directions. Traditionally the search for "harmonics" in the full sky cosmic ray distribution has been carried out in right ascension (RA) [9,10], owing to the nearly–uniform exposure in RA of ground array experiments. In the case of HiRes, exposure corrections will need to be taken into account due to the yearly fluctuations in the length of the nightly observing periods.

## 6. Conclusions

The results of the studies described in this paper will be presented at ICRC2003.

## 7. Acknowledgements

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