Monocular Anisotropy Studies with the Full HiRes-I Data Set

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Abstract: The High Resolution Fly's Eye HiRes-I detector has now been decommissioned after nearly nine years of operation. During that time span, HiRes-I accumulated a larger atmospheric exposure to Ultra-High Energy Cosmic Rays (UHECRs) above 10^{19} eV than any other experiment to date. The final, updated results of searches for dipole distributions oriented towards major astrophysical landmarks and small-scale clustering are presented. We conclude that the HiRes-I data set is, in fact, consistent with an isotropic source model.

Introduction

The observation of Ultra-High Energy Cosmic Rays (UHECRs) has now spanned over forty years. Over that period, many source models have been proposed to explain the origin of these remarkable events. In the past five years, theoretical models have been suggested that would potentially produce dipole distributions oriented towards M87 [7] or Centaurus A [9, 5]. In addition, the Akeno Giant Air Shower Array (AGASA) has reported findings suggesting a 4% dipole-like enhancement oriented towards the Galactic Center present in its events with energies around 10^{18} eV [10]. This result seemed to be corroborated by findings published by the Fly's Eye experiment in 1999 that suggested the possibility of an enhancement in the galactic plane also at energies around 10^{18} eV [8], and also by a re-analysis of data from the SUGAR array that was published in 2001 [6] that showed an enhancement in the general vicinity of the Galactic Center.

Additionally, over the past decade, the search for sources of Ultra-High Energy Cosmic Rays (UHECRs) has focused upon small scale anisotropy in event arrival directions. This refers to statistically significant excesses occurring at the scale of $\leq 2.5°$. The interest in this sort of anisotropy has largely been fueled by the observations of the Akeno Giant Air Shower Array (AGASA). In 1999 [11] and again in 2001 [12], the AGASA collaboration reported observing what eventually became seven clusters (six "doublets" and one "triplet") with estimated energies above $\sim 3.8 \times 10^{19}$ eV.

Our methods for detecting the presence of a dipole source model and small-scale clustering are based upon comparisons between the real data and a large quantity of events generated by our Monte Carlo simulation program. The simulated data possess the same aperture and exposure as the actual HiRes-I monocular data set. We show how the asymmetric angular resolution of a monocular air fluorescence detector can be accommodated in this method.

The HiRes-I Monocular Data

The current data set consists of all reconstructed events in the full HiRes-I monocular data set. This set contains the events observed between May 1997 and April 2006. There are 2332 events with reconstructed energies above $10^{18.5}$ eV and 79 events with reconstructed energies above $10^{19.5}$ eV. This represents a cumulative exposure of ~ 4500 km^2·sr·yr at 5×10^{19} eV..

In order to perform anisotropy analysis on this subset of data, we first parameterize the HiRes-I monocular angular resolution. For a monocular air fluorescence detector, angular resolution consists of two components, the plane of reconstruction, that is the plane in which the shower is observed, and the angle ψ within the plane of reconstruction

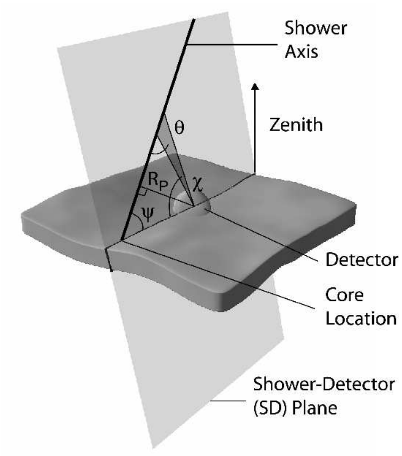

Figure 1: The geometry of reconstruction for a monocular air fluorescence detector

(see Figure 1). We can determine the plane of reconstruction very accurately. However, the value of ψ is more difficult to determine accurately because it is dependent on the precise results of the profile-constrained fit [1, 4].

The HiRes-I angular resolution is therefore described by an elliptical, two-dimensional Gaussian distribution. In Figure 2, the arrival directions of the HiRes-I events are plotted in equatorial coordinates along with their 68% error ellipses.

In order to understand the systematic uncertainty in the angular resolution estimates, we consider a comparison of estimated arrival directions that successfully reconstructed in both HiRes-I monocular mode and HiRes stereo mode. We consider all mono/stereo candidate events with estimated energies above $10^{18.5}$ eV. In stereo mode, the shower detector planes of the two detectors are intersected, thus the geometry is much more precisely known and the total angular resolution is of order $0.6°$. This allows us to perform a comparison of the angular resolution estimated through simulations to the observed angular resolution values of actual data. In Figure 3, we show the correlation histogram of the monocular versus stereo arrival direction estimates where each arrival direction is treated a Guassian distribution about its error space. By varying the size of the monocular error elipses for simulated data sets (Figure 3), we conclude that there is a $\sim 2.5\%$ systematic uncertainty in the angular resolution parameters.

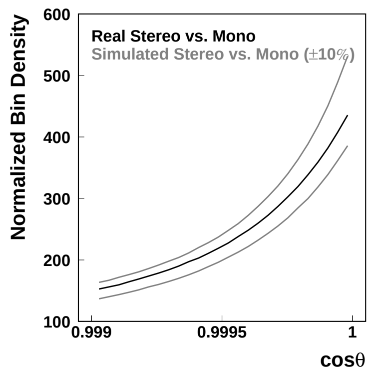

Figure 3: Correlation in the arrival direction error spaces between monocular and stereo reconstuctions for real and simulated data. For the two simualated data sets, the size of the monocular error elipses was fluctuated $\pm 10\%$.

Dipole Measurement Results

The method for measuring the anisotropy amplitude, α, for potential dipole sources is discussed at length in Abbasi *et al.* [3].

Analysis

In summary, we measure the value of the anisotropy amplitude by the following method:

1. We calculated the value of $<\cos\theta>$ for the dipole function of the real data sample.

2. We created a total of 20,000 simulated data samples, 1000 each for 0.1 increments of α from -1.0 to 1.0, each with the same number of events as the actual data.

3. We constructed curves corresponding to the mean and standard deviation of $<\cos\theta>$ of the dipole function for each value of α.

4. We determined the preferred value of α and the 90% confidence interval of α for each

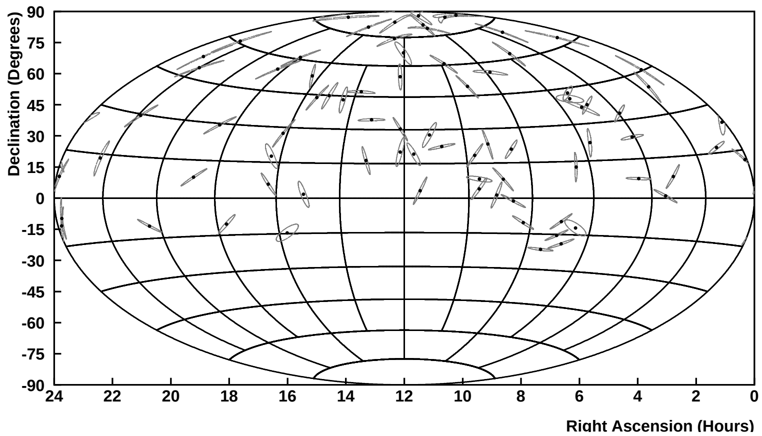

Figure 2: The arrival directions of the HiRes-I monocular data with reconstructed energies above $10^{19.5}$ eV events and their 68% angular resolution

Source	α
Galactic	-0.015 ± 0.040
Centaurus A	-0.020 ± 0.045
M87	-0.030 ± 0.040

Table 1: Estimation of α via the value of $<\cos\theta>$ for the dipole function.

dipole source model by referring to the intersections of the 90% confidence interval curves with the actual value of $<\cos\theta>$ for the dipole function of the real data.

The results are shown in Table 1. We are able to place upper limits on the value of $|\alpha|$ for each of our three proposed dipole source models. However, these limits are not small enough to exclude the theoretical predictions [7, 9, 5]. Also, they do not exclude the findings of the AGASA collaboration in terms of the intensity of the dipole effect that they observed or in terms of the energy considered because the events in the dipole effect observed by the AGASA detector possessed energies below $10^{18.5}$ eV [10].

Small-Scale Clustering Results

The method for measuring the small scale clustering is discussed at length in Abbasi *et al.* [2].

Analysis

We measure the degree of small-scale clustering by means of an autocorrelation function. It is calculated as follows:

1. For each event, an arrival direction is sampled on a probabilistic basis from the error space defined by the angular resolution of the event.

2. The opening angle is measured between the arrival directions of a pair of events.

3. The cosine of the opening angle is then histogrammed.

4. The preceding steps are repeated until all possible pairs of the events are considered.

5. The preceding steps are repeated until the error space, in the arrival direction of each event, is thoroughly sampled.

6. The histogram is normalized and the resulting curve is the autocorrelation function.

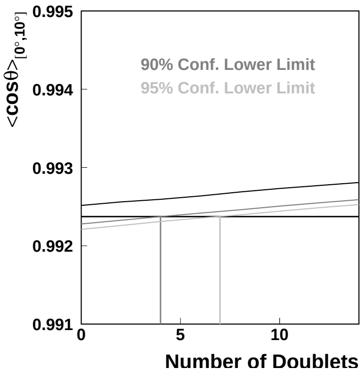

Figure 4: Sensitivity of the HiRes-I monocular observations to doublets. The horizontal line indicates the value of $<\cos\theta>_{[0^\circ,10^\circ]}$ for the observed data.

7. The autocorrelation function is quantified by calculating $<\cos\theta>$ for $\theta \leq 10^\circ$

Once we calculate $<\cos\theta>_{[0^\circ,10^\circ]}$ we can then study the clustering sensitivity of HiRes-I by additionally measuring the value of $<\cos\theta>_{[0^\circ,10^\circ]}$ for multiple simulated sets with a variable number of doublets inserted. We then construct an interpolation of the mean value and standard deviation of $<\cos\theta>_{[0^\circ,10^\circ]}$ for a given number of observed doublets. The results of this analysis are shown in Figure 4 In general, we state with a 90% confidence level that no more than 10.1% of the 79 observed events above $10^1 9$ eV have shared arrival directions.

Acknowledgments

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