The Search for Anisotropy in the Arrival Directions of Ultra-High Energy Cosmic Rays Observed by the High Resolution Fly's Eye Detector in Monocular Mode

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The High Resolution Fly's Eye HiRes-I detector has now been in operation in monocular mode for over six years. During that time span, HiRes-I has accumulated a larger exposure to Ultra-High Energy Cosmic Rays (UHECRs) above 10^{19} eV than any other experiment built to date. This presents an unprecedented opportunity to search for anisotropy in the arrival directions of UHECRs. We present results of a search for dipole distributions oriented towards major astrophysical landmarks and a search for small-scale clustering. We conclude that the HiRes-I data set is, in fact, consistent with an isotropic source model.

1. 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 [1] or Centaurus A [2,3]. 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 [4]. 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 [5], 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.

However, both AGASA and Fly's Eye are subject to a limiting factor; they are both located too far north in latitude to directly observe the Galactic Center itself. The re-analysis of SUGAR data actually demonstrated an excess that was offset from the Galactic Center by 7.5° and was more consistent with a point source than a global dipole effect [6]. While the current High Resolution Fly's Eye (HiRes) experiment is subject to a similar limitation in sky coverage as the AGASA and Fly's Eye experiments, we will show that, by properly estimating the HiRes aperture and angular resolution, we can effectively exclude these dipole source models to a certain degree of sensitivity. However, we are not able to completely exclude the findings of AGASA or the theoretical predictions mentioned above.

Additionally, over the past decade, the search for sources of Ultra-High Energy Cosmic Rays (UHECRs) has also begun to focus 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 [7] and again in 2001 [8], the AGASA collaboration reported observing what eventually became seven clusters (six "doublets" and one "triplet") with estimated energies above $\sim 3.8\times10^{19}$ eV. Several attempts that have

*See http://hires.phys.columbia.edu for a complete list of authors been made to ascertain the significance of these clusters returned chance probabilities of 4×10^{-6} [9] to 0.08 [10].

By contrast, the monocular (and stereo) analyses that have been presented by the High Resolution Fly's Eye (HiRes) demonstrate that the level of autocorrelation observed in our sample is completely consistent with that expected from background coincidences [11,12,13]. Any analysis of HiRes monocular data needs to take into account that the angular resolution in monocular mode is highly asymmetric.

It is very difficult to compare the results of the HiRes monocular and AGASA analyses. They are very different in the way that they measure autocorrelation. Differences in the published energy spectra of the two experiments suggest an energy scale difference of 30% [14,15]. Additionally, the two experiments observe UHECRs in very different ways. The HiRes experiment has an energy-dependent aperture and an exposure with a seasonal variability [14]. These differences make it very difficult get an intuitive grasp of what HiRes should see if the AGASA claim of autocorrelation is justified. In order to develop this sort of intuition, we apply the same analysis to both AGASA and HiRes data.

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.

2. The HiRes-I Monocular Data

The data set that we consider consists of events that were included in the HiRes-I monocular spectrum measurement [14,16]. This set contains the events observed between May 1997 and February 2003. There were 1526 events with reconstructed energies above $10^{18.5}$ eV and 52 events with reconstructed energies above $10^{19.5}$ eV observed during this time period. The data set represents a cumulative exposure of $\sim$ 3000 km^2·sr·yr at 5×10^{19} eV. This data was subject to a number of quality cuts that are detailed in the above-mentioned papers [14,16]. We previously verified that this data set was consistent with Monte Carlo predictions in many ways including impact parameter (R_p) distributions [14] and zenith angle distributions [17]. For this study, we presumed an average atmospheric clarity [18].

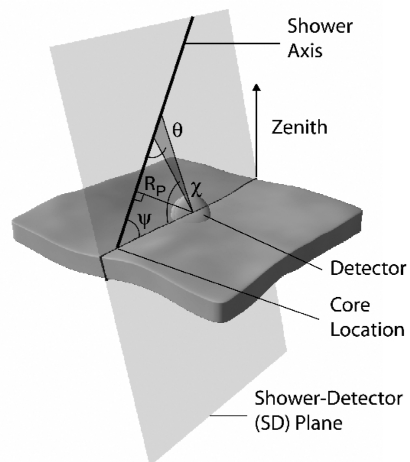

Figure 1. The geometry of reconstruction for a monocular air fluorescence detector

In order to perform anisotropy analysis on this subset of data, we must 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 (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 [14,16].

The HiRes-I angular resolution is therefore described by an elliptical, two-dimensional Gaussian distribution with the two Gaussian parameters, σ_ψ and σ_{plane}, being defined by the two an-

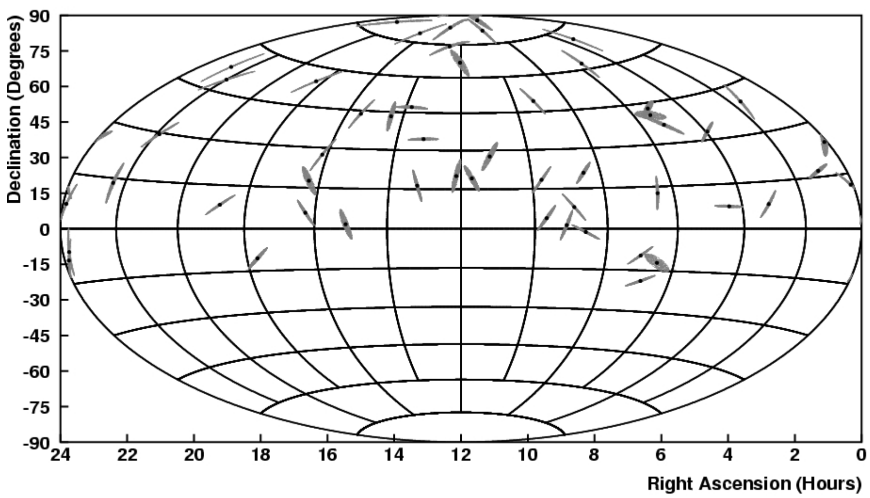

Figure 2. The arrival directions of the HiRes-I monocular data with reconstructed energies above $10^{19.5}$ eV events and their 1σ angular resolution

gular resolutions. For events with reconstructed energies above $10^{19.5}$ eV, $\sigma_{\psi} = [4.9, 6.1]^{\circ}$ and $\sigma_{\rm plane}[0.4, 1.5]^{\circ}$. In figure 2, the arrival directions of the HiRes-I events are plotted in equatorial coordinates along with their 1σ 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°, a number that is largely correlated to $\sigma_{\rm plane}$ and thus is negligible when added in quadrature to the larger term, σ_{ψ}. 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 distribution of angular errors for real and simulated data. The uncertainty in the slope of the ratio (figure 3b) leads to an 7.5% uncertainty in the angular resolution.

3. Dipole Measurement Results

The method for measuring the anisotropy amplitude, α, for potential dipole sources is discussed at length in Abbasi *et al.* [17].

3.1. 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 dipole source model by referring to the intersections of the 90% confidence interval

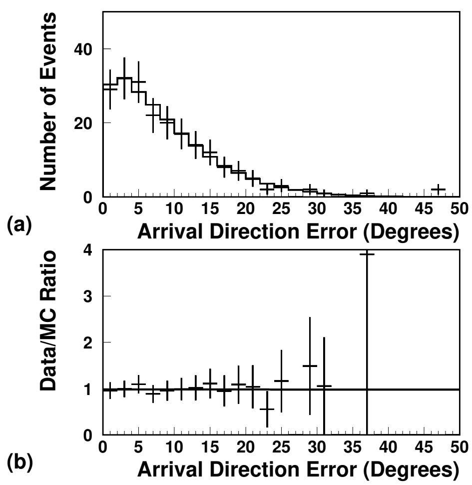

Figure 3. Arrival direction error comparison between real data (mono vs. stereo) and simulated data for events with estimated energies above $10^{18.5}$ eV. The solid line histogram corresponds to the arrival direction error distribution of the monocular reconstructed Monte Carlo simulated data. The crosses correspond to the arrival directions error distribution observed for actual data by comparing the arrival directions estimated by the monocular and stereo reconstructions. The solid line in the ratio component corresponds to the fit $y = ax + b$ where $a = 0.000 \pm 0.011$ and $b = 0.98 \pm 0.11$.

curves with the actual value of $<\cos\theta>$ for the dipole function of the real data.

The results are shown in table 1.

3.2. Conclusion

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 [1,2,3]. 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 be-

Source	α
Galactic	0.005 ± 0.055
Centaurus A	-0.005 ± 0.065
M87	-0.010 ± 0.045

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

cause the events in the dipole effect observed by the AGASA detector possessed energies below $10^{18.5}$ eV [4]. Since it appears that angular resolution has little impact on the measurement of α and we do not appear to be systematically limited, we conclude that the driving factor in making a better determination of α will simply be larger event samples. HiRes-I mono will continue to have the largest cumulative aperture of any single detector for the next three to five years, thus it will continue to serve as an ever more powerful tool for constraining dipole source models.

4. Small-Scale Clustering Results

The method for measuring the small scale clustering is discussed at length in Abbasi *et al.* [19].

4.1. 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.

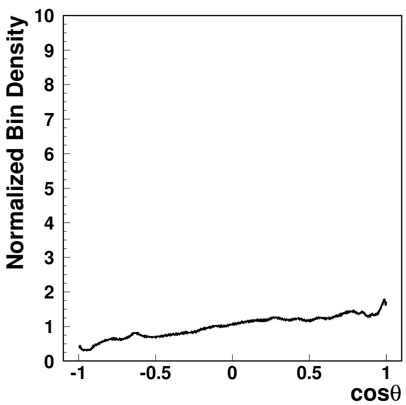

Figure 4. The autocorrelation for the HiRes-I events above $10^{19.5}$ eV.

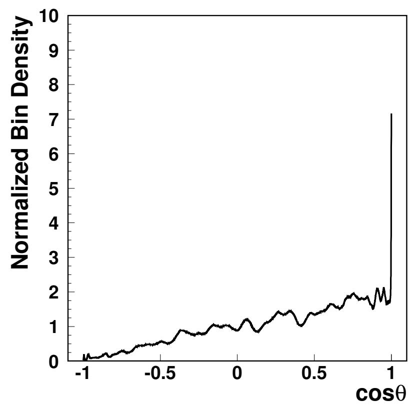

Figure 5. The autocorrelation for the published AGASA events [7].

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

A well-behaved measure of the autocorrelation of a specific set of data is the value of $<\cos\theta>$ for $\theta \leq 10°$. This value is also a measure of the sharpness of the autocorrelation peak at $\cos\theta = 1$. However, this method of quantification does not depend on bin width and it does produce Gaussian distributions when it is applied to large numbers of sets with similar degrees of autocorrelation. An additional advantage to this method is that by considering the continuous autocorrelation function over a specified interval, both the peak at the smallest values of θ and the corresponding statistical deficit in the autocorrelation function at slightly higher values of θ are taken into account. Thus we simultaneously measure both the positive and negative aspects of the autocorrelation signal.

Using the description of the HiRes-I monocular angular resolution above, we then calculate the autocorrelation function via the method described above. In figure 4, we show the result of this calculation. For this sample, we obtain $<\cos\theta>_{[0°,10°]} = 0.99234$.

We also calculate the autocorrelation function for the published AGASA events [7]. We show the result in figure 5. For this sample, we obtain $<\cos\theta>_{[0°,10°]} = 0.99352$.

To study the relative sensitivity of AGASA and HiRes-I, we measure the value of $<\cos\theta>_{[0°,10°]}$ for multiple simulated sets with a variable number of doublets inserted. We then construct an interpolation of the mean value and standard deviation of $<\cos\theta>_{[0°,10°]}$ from a given number of observed doublets for each experiment. This will allow us to state the number of doublets required for each experiment in order for the 90% confidence limit of $<\cos\theta>_{[0°,10°]}$ to be above the background value of 0.99250. In general, for a HiRes-I-like data set, the 90% confidence lower limit corresponds to the mean expected background signal with the inclusion of 6.25 doublets. For an AGASA-like, the 90% confidence lower limit corresponds to the mean expected background signal with the inclusion of 5.5 doublets. This demonstrates that while AGASA has a slightly better ability to perceive autocorrelation, the sensitivity of the two experiments is comparable. However, the observed HiRes-I signal corresponds to the 90% confidence upper limit with the inclusion of only 3.5 doublets beyond random background coincidence.

4.2. Conclusion

We conclude that the HiRes-I monocular detector sees no evidence of clustering in its highest energy events. Furthermore, the HiRes-I monocular data has an intrinsic sensitivity to global autocorrelation such that we can claim at the 90% confidence level that there can be no more than 3.5 doublets above that which would be expected by background coincidence in the HiRes-I monocular data set above $10^{19.5}$ eV. From this result, we can then derive, with a 90% confidence level, that no more than 13% of the observed HiRes-I events could be sharing common arrival directions. This data set is comparable to the sensitivity of the reported AGASA data set if one assumes that there is indeed a 30% energy scale difference between the two experiments. It should be emphasized that this conclusion pertains only to point sources of the sort claimed by the AGASA collaboration. Furthermore, because a measure of autocorrelation makes no assumption of the underlying astrophysical mechanism that results in clustering phenomena, we cannot claim that the HiRes monocular analysis and the AGASA analysis are inconsistent beyond a specified confidence level.

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