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Angular Correlation Estimates for Ultrahigh Energy Cosmic Rays

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Anisotropy in arrival directions of ultrahigh energy cosmic rays offers the most direct way to search for the sources of these particles. We present estimates of the angular correlation in the HiRes sample of stereo events above 10^{19} eV, and in the combined sample of HiRes and AGASA events above 4×10^{19} eV.

Keywords: ultrahigh energy cosmic rays; anisotropy of cosmic rays

1. Introduction

Identifying the sources of ultrahigh energy cosmic rays remains one of the major challenges in astrophysics. If these cosmic rays are not too severely deflected by magnetic fields while in transit, then their arrival directions will provide crucial information about their origins.

The High Resolution Fly's Eye (HiRes) experiment, consisting of two air fluorescence detector sites, has been making stereo observations of ultrahigh energy cosmic rays since 1999. The angular resolution ($\sim 0.6°$) achieved by this experiment sets the stage for the most precise measurements yet of small-angle correlation among the highest energy cosmic rays. In this paper we analyze HiRes events with energies above 10^{19} eV observed between 1999 December and 2004 January. More details about this data set are given in Ref. 1. We also analyze a combination of events from HiRes and from the Akeno Giant Air Shower Array (AGASA) with energies above 4×10^{19} eV.

2. Analysis

A standard tool for studying anisotropy is the angular two-point correlation function. We define the estimator for the correlation function as $w(\theta) = N(\theta)/\langle N_{mc}(\theta)\rangle - 1$, where $N(\theta)$ is the number of pairs of events in the data sample

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with angular separation less than θ, and $\langle N_{mc}(\theta)\rangle$ is the average number of such pairs in simulated isotropic sets with the same number of events and same detector acceptance in right ascension and declination as the data sample. Note that this definition of $w(\theta)$ is cumulative over angles up to θ. It reveals how the correlation signal varies as a function of the angular threshold for defining a pair.

Fig. 1(A) shows the angular correlation for the HiRes stereo events with energies above 10^{19} eV, along with the (Poisson) errors $\sqrt{N}/\langle N_{mc}\rangle$ (in general, the variance of correlation estimates may be larger than the Poisson variance). No significant excess of pairs is observed for any angular scale.

In 1999 and 2000 (Refs. 2, 3) the AGASA collaboration reported significant clustering among events above 4×10^{19} eV. In a set of 57 events, seven pairs were observed with angular separation less than 2.5°, against an expected $\langle N_{mc}\rangle = 1.5$ pairs, yielding $w(2.5°) = 3.7$. The probability for seven or more pairs evaluated using Monte Carlo is $\sim 0.1\%$. However, as has been noted in Ref. 4, this probability is not indicative of the statistical significance, because of bias introduced by the *a posteriori* choice of the energy threshold and angular separation.

The angular correlation estimate can be improved by combining the AGASA and HiRes data. By itself, the set of 27 HiRes events above 4×10^{19} eV has no pairs separated by less than 5°, yielding $w = -1$, but with large uncertainty. However, the combination of the two sets substantially increases the statistical power over either one individually, because of the cross-correlation power of the two sets.

To determine the expected number of pairs $\langle N_{mc}\rangle$, we simulate combined sets with 57 events generated using the AGASA acceptance and 27 generated using the HiRes acceptance. Although these acceptances are not identical, they have a large overlap; the resulting value of $\langle N_{mc}\rangle$ is in fact roughly comparable whether one uses all AGASA events, all HiRes events, or a combination.

The two detectors also have different angular resolutions. While this does not affect simulated isotropic sets, it could affect the correlation estimate for a real clustering signal: a clustering signal of higher significance could appear at smaller angular scales because the HiRes angular resolution is several times sharper than that of AGASA. However, since $w(\theta)$ includes all pairs with separations less than θ, this effect will not lead to a reduced signal at larger angles. Therefore rather than attempt to estimate the optimal scale for a clustering signal, for the sake of comparison we will continue to evaluate $w(2.5°)$ for the combined data set.

Figure 1(B) shows the results for the 57 AGASA events alone, and for the 84 AGASA and HiRes events evaluated jointly. The addition of the HiRes data brings one new pair with an AGASA event within 2.5°, yielding $N = 8$, $N_{mc} = 3.0$, and $w(2.5°) = 1.7$. The fraction of simulated sets with eight or more pairs is $\sim 1\%$, but it must be emphaiszed that this does not represent a chance probability because it includes the same bias in the AGASA data set noted above.[a] On the other hand,

[a] A similar but unbiased analysis using only the AGASA events observed after the choice of cuts (i.e. 27 AGASA and 27 HiRes events), results in $N = 2$, $N_{mc} = 1.2$ and $w(2.5°) = 0.7$, for a

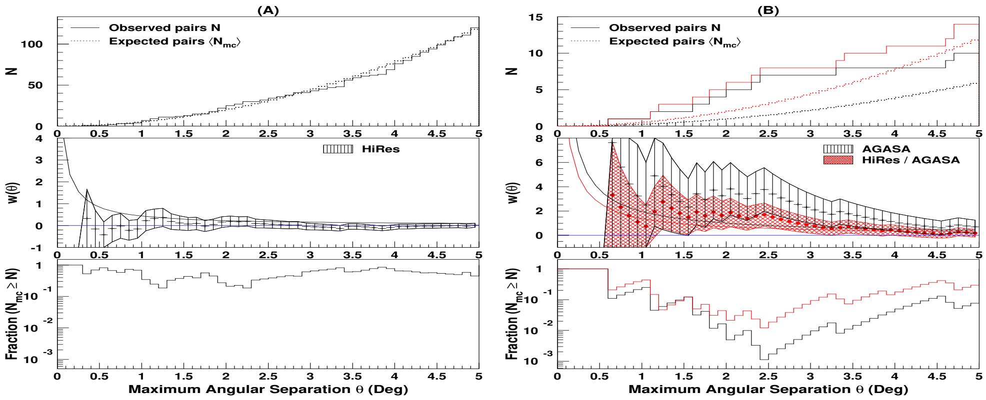

Fig. 1. A) the HiRes data set above 10^{19} eV and B) the AGASA and the combined HiRes/AGASA data sets above 4×10^{19} eV. Top: Number of observed (N) and expected $(\langle N_{mc}\rangle)$ pairs of events as a function of maximum separation angle θ. Middle: angular correlation w and associated uncertainty (see text) for an isotropic set (solid curve) and for the data set (vertical bars). Bottom: the fraction of simulated Monte Carlo sets with $N_{mc} \geq N$. Note: values of w in neighboring bins are correlated.

an observation of $w(2.5°) = 3.7$, as seen originally in the AGASA data alone, would have meant the observation of 14 pairs in the combined data set, corresponding to a 10^{-5} deviation from isotropy.

3. Conclusions

Angular correlation estimates for the HiRes events above 10^{19} eV reveal no significant deviations from isotropy at any small angle. Combining HiRes and AGASA events above 4×10^{19} eV improves the statistics above this threshold relative to the AGASA data set alone, and results in substantially reduced angular correlation.

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chance probability of 34%. Details will be presented in a separate paper.