STUDY OF SMALL-SCALE ANISOTROPY OF ULTRAHIGH ENERGY COSMIC RAYS OBSERVED IN STEREO BY HIRES

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ABSTRACT

The High Resolution Fly’s Eye (HiRes) experiment is an air fluorescence detector which, operating in stereo mode, has a typical angular resolution of 0.6° and is sensitive to cosmic rays with energies above 10^{18} eV. HiRes is thus an excellent instrument for the study of the arrival directions of ultrahigh energy cosmic rays. We present the results of a search for anisotropies in the distribution of arrival directions on small scales (< 5°) and at the highest energies (> 10^{19} eV). The search is based on data recorded between 1999 December and 2004 January, with a total of 271 events above 10^{19} eV. No small-scale anisotropy is found, and the strongest clustering found in the HiRes stereo data is consistent at the 52 % level with the null hypothesis of isotropically distributed arrival directions.

Subject headings: cosmic rays — acceleration of particles — large-scale structure of universe

1. INTRODUCTION

Identifying the sources of ultrahigh energy cosmic rays remains one of the central challenges in astrophysics. After three decades of systematic searches for the origin of these particles, source identification still remains elusive. Sky maps of cosmic ray arrival directions at all energies are generally isotropic, with no obvious source or source region standing out.

A direct way to search for sources of ultrahigh energy cosmic rays is to analyze the distribution of their arrival directions for small-scale clustering. Any significant clustering in arrival directions could be evidence of nearby, compact sources, whereas the lack of clustering is consistent with models in which ultrahigh energy cosmic ray sources are distributed at large distances from our Galaxy.

Arrival directions do not necessarily point back to sources, as charged cosmic ray primaries suffer deflections traveling through Galactic and intergalactic magnetic fields. The strength and orientation of these fields is not well established, so the size and direction of the deflection is difficult to ascertain. However, since the Larmor radius increases with energy, the possibility of observing small-scale anisotropy associated with cosmic rays pointing back to their origins is expected to grow.

Indeed, small-scale clustering of cosmic ray arrival directions at the highest energies has been previously claimed. The AGASA (Akeno Giant Air Shower Array) experiment reported possible clustering in their sample of events with energies above 4 \times 10^{19} eV [Havashida et al. 1996]. The analysis has been updated several times [Takeda et al. 1999, 2001; Teshima et al. 2003], most recently reporting six clusters (five doublets and one triplet) in a sample of 59 events, where a cluster is defined as a set of events with angular separation less than 2.5°. The chance probability of this signal was reported to be less than 10^{-4} [Teshima et al. 2003].

Given the potential importance of this result for our understanding of the origin of cosmic rays, it is crucial to test the claim that clustering is a feature of cosmic ray arrival directions with independent experimental data. Since 1999, the High Resolution Fly’s Eye (HiRes) air fluorescence experiment has been operating in stereo mode, collecting data of unprecedented quality on the arrival direction, energy, and composition of ultrahigh energy cosmic rays. In this Letter, we report results of a search for small-scale anisotropy in the arrival directions of ultrahigh energy cosmic rays observed by the HiRes stereo detector between 1999 December and 2004 January.

2. THE HIRES DETECTOR

HiRes is an air fluorescence experiment with two sites (HiRes 1 & 2) at the US Army Dugway Proving Ground in the Utah desert (112° W longitude, 40° N latitude, vertical atmospheric depth 860 g/cm²). The two sites are separated by a distance of 12.6 km.

Each of the two HiRes “eyes” comprises several tele-
scope units monitoring different parts of the night sky. With 22 (42) telescopes with 256 photomultiplier tubes each at the first (second) site, the full detector covers about 360° (336°) in azimuth and 3° − 16.5° (3° − 30°) in elevation above horizon. Each telescope consists of a mirror with an area of about 5 m² area for light collection and a cluster of photomultiplier tubes in the focal plane.

A cosmic ray primary interacting in the upper atmosphere induces an extensive air shower which the detectors observe as it develops through the atmosphere. The photomultiplier tubes triggered by the shower define an arc on the sky, and, together with the position of the detector, the arc determines the so-called shower-detector plane. When an air shower is observed in stereo, the shower trajectory is in principle simply the intersection of the two planes. This method can be further improved by also taking advantage of the timing information of the tubes, and in our analysis the shower geometry is determined by a global χ² minimization using both the timing and pointing information of all tubes. From measurements of laser tracks and stars in the field of view of the cameras we estimate that the systematic error in the arrival direction determination is not larger than 0.2°, mainly caused by uncertainties in the survey of mirror pointing directions.

Various aspects of the HiRes detector and the reconstruction procedures are described in Boyer et al. (2002); Sadowski et al. (2002); Matthews et al. (2003).

3. THE HIRES DATA SET

While a ground array detector can operate year-round, night and day, air fluorescence detectors can only be operated on dark, moonless nights with good atmospheric conditions. This limits the duty cycle to about 10%. However, several years of observation yield a data set with a relatively smooth distribution in sidereal time, modulated by an overall seasonal variation in exposure.

For the present analysis, we subject the HiRes stereo event sample to the following quality cuts. We require a minimum track length of 3° in each detector, an estimated angular uncertainty in both azimuth and zenith angle of less than 2°, and a zenith angle less than 70°. We additionally require an estimated energy uncertainty of less than 20% and χ²/dof < 5 for both the energy and the geometry fit. Weather conditions which reduce the quality of the data are cut implicitly in the above sample, rather than by explicit weather cuts. A total of 271 events above 10¹⁹ eV pass the selection criteria. A sky map in equatorial coordinates of the arrival directions of these events is shown in Figure 1.

The angular resolution of HiRes is determined using simulated showers. We use a full detector simulation of proton showers generated with CORSIKA 6 (Heck et al., 1998) using QGSJET for the first interaction. Applying the same cuts to the simulation data which are applied to the real data, 68% of all showers generated at 10¹⁹ eV are reconstructed within less than 0.57° of the true shower direction. The angular resolution depends weakly on energy, with the 68% error radius growing to 0.61° and 0.69° for showers generated at 4 · 10¹⁹ eV and 10²⁰ eV, respectively, because at higher energy, showers are on average farther away. The angular resolution is essentially constant in zenith and azimuth angle of the arrival direction, varying by less than 0.1°.

Using the same simulation described above, we generate an isotropic distribution of showers with a differential spectral index α = −3.0 in energy, and use the resulting distribution of reconstructed Monte Carlo events to determine the detector acceptance in zenith and azimuth. We then randomly match the local coordinates of these events with times during which the detector was operating in order to generate an exposure map in equatorial coordinates. Figure 2 shows the distributions of the data and Monte Carlo events in right ascension and declination.

4. METHOD

We search for small-scale clustering by performing an auto-correlation scan in energy and angular separation. Essentially, we consider the set of N events above energy E, count the number of pairs n_p separated by less than θ, and evaluate the probability P(N, θ) of finding this number or more pairs, given N and θ. We repeat this for a range of values for E and θ, and use the smallest probability P_min found in the scan to identify the strongest clustering signal. We estimate the statistical significance P_ch of this signal by performing identical scans over simulated sets of isotropically distributed data, counting the fraction of simulated sets which yield the same or smaller value for P_min.

The virtue of this approach is that by letting the energy threshold vary, we let the scan itself determine the optimal balance between the better statistics of the low energy data set and the (presumably) smaller angular deflections at high energies. Furthermore, we can simultaneously look for clustering both at the angular scale identified by AGASA and at smaller scales that take advantage of the HiRes angular resolution. The statistical penalty for performing multiple searches is accounted for in the final evaluation of the significance P_ch.

We note that, just as in the usual two-point correlation function, higher-order multiplets are counted by the individual number of pairs which they contain.

To determine the probabilities P(N, θ), we generate a large number of simulated data sets (typically 10⁷) corresponding to an isotropic distribution of cosmic rays. Specifically, we generate an event with a random arrival direction in equatorial coordinates, and accept that event into the simulated data set with a probability proportional to the HiRes exposure in that region of the sky. We then construct a table of values P_Mc, where P_Mc(N, θ, n) is the fraction of data sets in which the first N events contain exactly n pairs separated by less than θ. Then the probability P(N, θ) for observing n_p or more pairs at (N, θ) is simply:

\[
P(N, θ) = \sum_{n=n_p}^{∞} P_{MC}(N, θ, n) = 1 - \sum_{n=0}^{n_p-1} P_{MC}(N, θ, n).
\]

For some combination N_e and θ_e, P has a minimum: P_min = P(N_e, θ_e). We identify this as the strongest potential clustering signal. To determine the statistical significance, we perform the same scan over n_Mc Monte Carlo data sets, finding the minimum probability P_min = P(n_Mc, θ_e) for each trial and counting the number of trials n_{MC}^* for which P_{min} ≤ P_min. The sig-

\[
\]
that is, the chance probability of observing the value
of significance is finally identified as:

\[ P_{ch} = \frac{n_{MC}}{n_{MC}}, \]

that is, the chance probability of observing the value
of the 1% significance level. The table also shows that three such pairs among
the 47 highest energy events would typically result in
of the simulated sets. The table shows, for example, that for a clustering signal on the \( \sigma_R = 0.6^\circ \) scale, even three pairs among
the 47 highest energy events would typically result in
of the 90th percentile values of this distribution are indicated in Table 1.

The table shows, for example, that for a clustering signal on the \( \sigma_R = 0.6^\circ \) scale, even three pairs among
the 47 highest energy events would typically result in
of the simulated sets. Thus, an actual value of \( P_{ch} > 6.7\% \) could be used to exclude the possibility that sources contributed three such pairs at more than the 90% confidence level.

These results demonstrate the sensitivity to clustering on small angular scales.

5. RESULTS AND DISCUSSION

We perform the scan on the HiRes stereo sample of
271 events above \( 10^{19} \) eV. Because we start well below
the \( 4 \cdot 10^{19} \) eV energy associated with the AGASA clustering signal, our search should safely encompass the en-

Fig. 1.— Skymap (in equatorial coordinates) of the 271 HiRes stereo events above \( 10^{19} \) eV examined in this study. The typical error
radius of 0.6° is used for all events.

Fig. 2.— Right ascension and declination of events above \( 10^{19} \) eV observed from 1999 December through 2004 January. (Data—
points with error bars; Monte Carlo—solid line.) For right ascension, \( \chi^2/\text{dof} = 0.77 \); for declination, \( \chi^2/\text{dof} = 0.73 \).
energy region of interest even in the presence of a systematic energy shift of 30% between the two experiments, as suggested by Boyer, J. et al. 2002, Nucl. Instr. Meth. A, 482, 457.

Comparing the observed value of $P_{ch}$ with the values obtained from simulations in Section 4 (shown in Table 1), we note that if the current HiRes data above $4 \cdot 10^{19}$ eV contained two or more pairs of events contributed by compact sources at the angular resolution limit of the detector, then the typical value of $P_{ch}$ would be 0.018 or less, and more than 90% of the time the value of $P_{ch}$ would be much smaller than the observed value of 0.52.

Results of searches for correlations with known astrophysical source classes will be published in a separate paper.

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