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Search for Pointlike Sources of Cosmic Rays with Energies above $10^{18.5}$ eV in the HiRes–I Monocular Dataset

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We report the results of a search for pointlike deviations from isotropy in the arrival directions of ultra–high energy cosmic rays in the northern hemisphere, using the monocular dataset collected by the High–Resolution Fly's Eye. This dataset consists of 1,525 events with energy exceeding $10^{18.5}$ eV.

1. Introduction

In the search for the origins of ultra–high energy cosmic rays (UHECR), a variety of strategies have been employed to detect deviations from isotropy in event arrival directions. The results of these searches have been ambiguous. The most recent results [1] have supported the null hypothesis for large–scale dipole behavior in arrival directions for particles above $10^{18.5}$ eV. However, previous experiments [2] have found evidence for a dipole moment in Right Ascension (RA) at energies above 10^{18} eV. On smaller angular scales, excesses have been alternately claimed and refuted in the vicinity of Cygnus X-3 [3, 4, 5, 6], an x-ray binary within our galaxy, including the report of a possible excess in a point-source search [7].

Point-like excesses at these energies can arise from only a limited number of source scenarios. Galactic and extragalactic magnetic fields are expected to produce large perturbations in the arrival directions of charged particles: A proton of energy $10^{18.5}$ eV may be deflected by several tens of degrees as it traverses the disk of the Milky Way galaxy, with a typical magnetic field of order 1 microgauss [8]. A compact arrival direction excess at these energies would therefore suggest neutral primaries. Neutrons however possess a lifetime of 3×10^{12} seconds at $10^{18.5}$ eV, and therefore cannot have originated more than 30 kpc from Earth. Thus any viable source of standard model neutral hadronic matter would have to be located within the Milky Way Galaxy.

In this paper, we conduct a search for point-like behavior in arrival direction of cosmic ray events above $10^{18.5}$ eV in the northern hemisphere, using a skymap technique in which we evaluate our sensitivity using Monte Carlo simulated sources. In addition, we consider the historically significant source candidate Cygnus X-3 as the focus of an *a priori* search.

2. The HiRes Monocular Data Set

The High–Resolution Fly's Eye (HiRes) consists of two nitrogen fluorescence observatories — HiRes–I and HiRes–II — separated by 12.6 km and located at Dugway, Utah. HiRes was conceived as a stereo detector, however due to the larger available statistics it is desirable to reconstruct extensive airshowers in monocular mode as well. This HiRes–I monocular data set consists of 2,820 good–weather detector hours of data, collected between May 1997 and February 2003. A total of 1,525 events with energies exceeding $10^{18.5}$ eV were collected during this time and are included in the present analysis.

The HiRes-I monocular data set and airshower reconstruction by profile constrained fitting has recently been described in the literature [9]. A residual effect of the profile–constrained fit technique is orientation–dependent

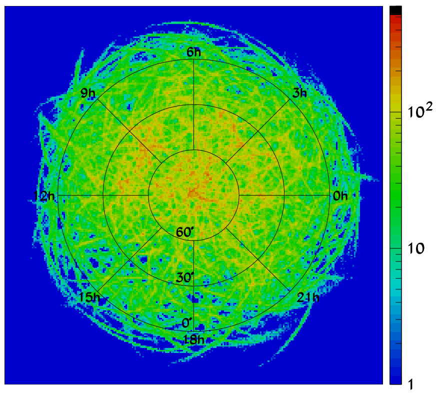

Figure 1. Skymap of arrival directions of events in the the HiRes–I monocular data set, plotted in polar projection, equatorial coordinates. Each HiRes event is represented by 1,000 points randomly thrown according to the elliptical Gaussian error model. The bin size in this plot (and all similar plots) is approximately $1^\circ \times 1^\circ$.

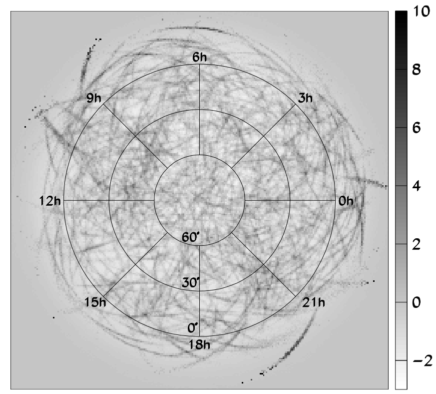

Figure 2. χ_1 (Equation 1) distribution for the HiRes-I monocular data set.

(elliptical) uncertainties in the airshower arrival directions. The shower–detector plane (SDP) for HiRes–I events is well–reconstructed. Typical values of σ_{SDP} for this analysis range from $0.4^\circ \rightarrow 1.7^\circ$. The angle of the track within the SDP, Ψ, is less well reconstructed. Typical values of σ_Ψ in this analysis range from $5.4^\circ \rightarrow 15^\circ$.

In Figure 1, we plot the skymap formed from the arrival directions of events in the present data set. Each event's "error ellipse" is represented by generating 1,000 points per event, distributed according to the Gaussian error model of the Equations. Figure 1 is plotted in equatorial coordinates as a polar plot. Note that bins are assigned using a Cartesian projection of the polar plot shown in Figure 1 and all similar figures. As such, angular bin size varies across the map, but averages approximately $1^\circ \times 1^\circ$.

We next discuss the Monte Carlo technique by which we evaluate the significance of fluctuations in the skymap as well as our sensitivity to point-like behavior in arrival direction.

3. The Monte Carlo; Comparison of Data to Expectation from an Isotropic Background

We use a library of simulated events, generated by the Monte Carlo technique and reconstructed using the profile–constrained reconstruction program to determine the background expectation for isotropically distributed sources as well as to evaluate our sensitivity to point-like behavior in arrival direction. For this library, an isotropic distribution is assumed for events possessing the spectrum and composition reported by the stereo Fly's Eye experiment [10, 11].

A detector runtime database is used to randomly assign a time from detector "on" periods to each event in the isotropic background data set. A total of 1,000 isotropic data sets with the same sky exposure as the HiRes–I monocular data set were generated for comparison studies. Further discussion of this Monte Carlo can be found in Reference [1].

In order to understand the significance of the fluctuations in Figure 1, we compare the data on a bin-by-bin basis to the 1,000 simulated data sets. Defining N_{DATA} as the bin density of the data, N_{MC} as the bin density of the simulated isotropic data sets, and σ_{MC} as the standard deviation of the Monte Carlo bin density, the variable

$$\chi_1 = \frac{(N_{DATA} - \langle N_{MC} \rangle)}{\sigma_{MC}} \quad (1)$$

provides a measure of the fluctuation per bin. Figure 2 shows the distribution of χ_1 as a function of position in the sky for the HiRes–I monocular data set as extracted from this technique.

The bin-by-bin distributions of χ_1 are non-Gaussian and vary as a function of position in the sky. Thus it is necessary to develop a technique to evaluate the significance of possible sources. Our technique uses the χ_1 information in neighboring bins to pick out significant fluctuations above background from the skymap. The parameters in the technique are tuned on simulated point-like sources.

4. The Monte Carlo; Simulation of Point-Like Sources

We have two objectives in simulating point-like sources: The first is using these simulated sources to tune point source selection criteria. Secondly, simulated sources provide a straightforward method by which to quantify our sensitivity to point-sources and derive flux upper limits.

Simulated source skymaps are created by randomly replacing events in a simulated isotropic data set with N_S events at the chosen position for the source. The central-value coordinates of the simulated source event are randomly shifted according to the error ellipse, which is taken from the replaced event. The shift simulates the effect of detector resolution only. Finally, the orientations of error ellipses are randomized.

5. Calculation of Significances

We now describe a procedure by which we can identify point-like behavior in arrival direction while simultaneously rejecting false positives arising from fluctuations of the background.

Due to detector resolution, it is desirable that we search for sources by considering points over an extended angular region. We consider a “search circle” of radius R, where R is expressed as an angle in degrees. Within the search circle, we count the fraction of bins F having a χ_1 value greater than some threshold χ_{THR}. The parameters R and χ_{THR} are chosen to optimize the signal size, and a cut is chosen on the fraction F which reduces the false positive probability to an acceptable level.

Our maximum sensitivity to point-like behavior in arrival direction, given the HiRes–I pointing uncertainty, was determined to require a search circle of $R = 2.5°$, and a value $\chi_{THR} = 4$. (In the case in which the bin densities are normally distributed, this corresponds to 4σ.) The optimum values for these parameters were determined by simulating sources at various locations in the sky and maximizing our sensitivity to these sources. The values for these parameters are found to be largely insensitive to the position in the sky and the number of events in the source. Additionally, small variations in either of these parameters do not have a significant impact on our results.

Due to low statistics at the edge of HiRes’ acceptance, we consider only search circles with centers whose declinations are greater than $0°$. That is, we only search for sources north of the celestial equator. Approximately

10% of HiRes events have central-value coordinates south of the equator. These events can contribute to the search if their error ellipses extend north of DEC $= -2.5°$. The final parameter in this search algorithm is the cut placed on the quantity F. We evaluate this cut by requiring that the probability of a simulated isotropic data set – *without* a superimposed simulated source — exceeding the cut be no more than 10% over the entire sky. We choose a cut value of $F = 0.33$, corresponding to a false–positive probability of 10%.

6. Sensitivity and Upper Limits

To set upper limits based on our observations, we follow the suggestion of Feldman and Cousins [12] and calculate both a set of flux upper limits and the "sensitivity" of the experiment to such point-like excesses. The sensitivity of the experiment is defined as the average 90% confidence level flux upper limit that would be reported by an ensemble of like experiments with no true signal. Since this average upper limit will vary as a function of position on the skymap due to different background expectations, we calculate our sensitivity at set of grid points distributed evenly across the Northern Hemisphere. We place our 90% confidence level flux upper limits by making use of the maximum value of F observed in the HiRes-I data. These limits are reported at the same set of grid points.

7. Conclusions

The results of the studies described in this paper will be presented at ICRC2005.

8. Acknowledgements

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