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Anisotropy studies of ultra-high energy cosmic rays as observed by the High Resolution Fly's Eye (HiRes)

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Abstract. Although the existence of cosmic rays with energies extending to 320 EeV has been confirmed , their origin remains one of the most important questions in particle astrophysics research today. The High–Resolution Fly's Eye (HiRes) is the largest aperture detector currently collecting data from ultra-high energy cosmic ray events. We present for the first time anisotropy studies from monocular and stereo data collected by HiRes. We consider topical candidate sources including the supergalactic plane , the Virgo cluster of galaxies , Cygnus X-3 and the vicinity of the AGASA triplet. We also present the results of searches for density fluctuations as well as autocorrelation studies of cosmic ray arrival directions in the absence of a priori candidate sources. Finally, we present the results of a search for harmonics in the full-sky event distribution.

1 Introduction

The High–Resolution Fly's Eye (HiRes) has been collecting data in monocular mode since 1997 and in stereo mode since 1999. Analysis on the monocular data is well underway, and we present here for the first time the results of several anisotropy analyses on the monocular data set. We also discuss potential improvements to these analyses which will result from the accumulation of high–statistics stereo data.

2 Shower Density Sky Maps

The technique of creating shower density sky maps is useful for studying the region of sky around candidate source regions. In producing these maps we incorporate the estimated arrival direction errors for each event, and make use of a "shuffling" technique to take account of the non-uniform exposure of the HiRes detector. We make use of the data itself to estimate the significance of any excess or deficit in shower density. The techniques as applied here were developed for use with Fly's Eye data (Cassiday et al., 1990), and have also been applied to data from other experiments, (e.g. Bellido et al. (2001)).

The geometry of events used in this analysis have been determined using a profile-constrained mono fit (Abu-Zayyad et al., 1997). Briefly, this involved using the projection of the directions of firing pixels onto the celestial sphere to define the "shower-detector plane" (SDP), that plane containing the shower axis and a point representing the detector. The orientation of the shower axis within the SDP (defined by the impact parameter R_p and the ground angle ψ within the plane) is determined from pixel timing information constrained by a requirement that the reconstructed shower development profile have parameters within certain expected bounds.

Thus each event in our data set has a nominal arrival direction, with uncertainties in that direction expressed in terms of an uncertainty in the orientation of the SDP's normal vector and an uncertainty in the track angle ψ within the plane. For the sky map we represent each event by a gaussian probability function surrounding its nominal direction on the sky. The gaussian has, in general, a different width in each of the orthogonal directions. One dimension is largely determined by the uncertainty in the SDP normal, and the other is determined by the uncertainty in ψ. The SDP is usually reconstructed with better precision than the track within the plane, resulting in an elongated two-dimensional gaussian, with its major axis oriented along a line defined by the projection of the SDP onto the sky. Each error gaussian is normalized so that its total "volume" is unity, before being added to the sky map. The sky map thus consists of the sum of all event gaussians, producing a map of shower density that takes into account our estimates of reconstruction uncertainties. We call this the "density map".

We next compare this map with the expectation based on an isotropic flux of cosmic rays. That expectation must take into account the exposure of HiRes in right ascension and declination. It is determined using the "shuffling" technique (Cassiday et al., 1990). Here, a number of shuffled data sets

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are derived from the real data set, with each shuffled data set containing the same number of events as the real one. A real arrival time (Julian date) from one event is randomly paired with a local arrival direction (defined by the ψ angle and the SDP normal vector, together with errors in those parameters) from another event in the real data set. This is repeated until a new data set is filled. The new data set has the same arrival time distribution and the same distributions of local arrival directions as the real data set. However, because the pairings have been randomized, all celestial directions have been randomized simulating an isotropic event flux. Many shuffled data sets can be generated. For each of those, an event density map can be generated using 2D gaussian point-spread functions. An average of many such maps (typically 1000, but this depends on the number of events in the data set) provides a convenient and solid representation of the expectation for a flux of isotropic cosmic rays.

Comparing the real density map with the isotropic expectation, we can derive a map showing the fractional excesses and deficits of event densities across the sky. To compute the significance of any excess or deficit, we again use the shuffled data sets. We grid the original shower density map into small ($0.5°$) bins, and ask how many of the shuffled data sets have a shower density in the bin equal to or larger than the real bin density. Given that each shuffled map is a representation of an isotropic cosmic ray flux, this gives us a bin-by-bin probability that the real map density has occurred by chance. This gives us a map of significance across the sky, with regions of excess having chance probabilities less than 0.5, and regions of deficit having chance probabilities greater than 0.5.

3 Topical Sources

In addition to the results of shower density sky maps, we present the results of searches for sources of ultra–high energy cosmic rays in the vicinity of a preselected set of topical candidate “objects”. The technique consists of comparing the density of airshower arrival directions in the vicinity of the candidate objects with the density expected from an isotropic distribution given our detector exposure.

The first source we consider as a possible candidate is Cygnus X–3, which has been identified with a possible excess of cosmic rays in the ≥ 1 EeV range (Cassiday et al., 1989; Teshima et al., 1990).

AGASA recently reported clusters of events including several “Doublets” and one “Triplet” (Hayashida et al., 2000). We will report on the results of a HiRes search for events in the vicinity of the “Triplet” at energies exceeding 4×10^{19} eV.

We also consider the galaxy M-87 (Virgo A) (Biermann et al., 2000), due to the recent theoretical interest identifying it as a potential nearby source within the distance constraint imposed by the GZK cutoff (Greisen, 1966; Zatsepin and Kuz’min, 1966). For this source, we consider only events with energies exceeding 4×10^{19} eV. Of related interest is the extended source in the vicinity of the Supergalactic Plane (Stanev et al., 1995; Kewley et al., 1996).

4 Autocorrelation Studies

Autocorrelation makes use of the distribution of space angles between pairs of events. If the observed events are arriving from distinct point sources, one will see an enhancement in the autocorrelation function at small space angles.

One can create an autocorrelation function for a given event sample using the following methodology: (1) Take any pair of events. (2) Calculate the cosine of the space angle between the events. (3) Enter that value into a histogram of the cosine of the space angle. (4) Repeat until every possible event pairing has been considered.

In the present case however, the monocular profile constraint fit produces large asymmetric errors. However, one can treat each event as a two dimensional, asymmetric gaussian distribution of randomly generated points about its error space. One can then compare the distributions of the pairs of randomly generated points on a one-to-one basis. If one then repeats this for all possible pairings, one can create an autocorrelation function that accommodates large, asymmetric errors.

There are two background features that one must consider when doing autocorrelation studies with HiRes1 monocular data: asymmetric sky coverage and random coincidences. These background features can be accommodated by using the time shuffling technique described above. Further, simulated data sets generated by the time shuffling technique can be used to calculate a significance for each bin in the autocorrelation function of the real data.

5 Full–Sky Harmonic Analysis

In addition to searching for particular sources, we wish to determine whether or not large–scale patterns exist in cosmic ray arrival directions. Traditionally the search for “harmonics” in the full sky cosmic ray distribution has been carried out in right ascension (RA) (J. Linsley, 1975; P. Sokolsky et al., 1992), owing to the nearly–uniform exposure in RA of ground array experiments. In the case of HiRes, exposure corrections will need to be taken into account due to the yearly fluctuations in the length of the nightly observing periods.

A Rayleigh vector (x, y) is formed from a data set as follows:

$$x = \frac{2}{n} \sum_{i=1}^{n} \cos(\alpha_i) \qquad (1)$$

$$y = \frac{2}{n} \sum_{i=1}^{n} \sin(\alpha_i) \qquad (2)$$

where n is the number of showers in the data set and α_i is the RA of the i^{th} shower. The length of the vector $r =$

$\sqrt{x^2+y^2}$ is related to the chance probability

$$P(\geq r) = e^{-r^2/r_0^2} \tag{3}$$

($r_0 = 2/\sqrt{n}$) of obtaining a Rayleigh vector with length $\geq r$. The first harmonic phase is given by the direction of the Rayleigh vector.

The analysis of higher–order harmonics is carried out by substitution of $m\alpha_i$ in the Rayleigh vector components, where m is the order of the harmonic. Corrections due to detector exposure are taken into account by reweighing Rayleigh vector components according to the distribution in RA of the sidereal time "shuffled" data sets as described above.

6 Conclusions

The results of the studies described in this paper will be presented at ICRC2001.

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