Measurement of the Flux of UHE Cosmic Rays by the HiRes Detectors Observing in Monocular Mode

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Abstract

The HiRes experiment consists of two detectors located 12.6 km apart in the desert of west-central Utah that observe the showers initiated by UHE cosmic rays using the atmospheric fluorescence technique. We present a measurement of the flux of UHE cosmic rays made by the two HiRes detectors observing in monocular mode. The details of data collection, calibration, analysis, Monte Carlo development, aperture determination, and flux calculation will be presented.

1. Introduction

Ultra high energy cosmic rays (UHECRs) are interesting in that they shed light on two important questions: the nature of their origin in astrophysical or other sources and their propagation to us through the intragalactic medium. The production of pions from interactions of microwave background photons and UHECRs is an important energy loss mechanism above $10^{19.8}$ eV, and leads to the prediction of the Greisen-Zatsepin-K'uzmin (GZK) cut-off[10, 17]; e^+e^- production is a lesser energy-loss mechanism above a threshold of $10^{17.6}$ eV. We report here the flux of UHECRs from $10^{17.3}$ eV to over 10^{20} eV, measured in monocular mode, with the two High Resolution Fly's Eye (HiRes) detectors.

2. Analysis Techniques

Determination of the shower geometry is possible using a single detector (i.e. in monocular mode) by fitting the photo-tube trigger times to their viewing angles. However, HiRes-I events are too short in angular spread for reliable determination of the angle and imparact parameter by timing alone. For the HiRes-I analysis, the expected form of the shower development itself was used to constrain the time fit to yield realistic geometries. The shower profile is assumed to be described by the Gaisser-Hillas parameterization[9], which is in good agreement with previous HiRes measurements[2] and with CORSIKA/QGSJET simulations[15, 11, 13]. This technique is called the Profile-Constrained Fit (PCF).

Monte Carlo (MC) studies were performed to assess the reliability of the

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PCF method. The simulated events were subjected to the same selection criteria and cuts imposed on the data. Not including atmospheric fluctuations, an RMS energy resolution of better than 20% was seen above $10^{19.5}$ eV. However, the resolution degrades at lower energies to about 25% at $10^{18.5}$ eV. These MC results were cross-checked by examination of a smaller set of stereo events where the geometry is more precisely known. Comparing the energies reconstructed using monocular and stereo geometries, we obtained resolutions similar to those seen in MC.

The MC is also used to calculate the detector aperture. Simulated events were subjected to the same reconstruction algorithm and cuts applied to the data. To verify the reliability of this calculation, we compared, at different energies, the zenith angle and impact parameter distributions, which define the detector aperture. The MC predictions for these are very sensitive to details of the simulation, including the detector triggering, optical ray-tracing, signal/noise, and the atmospheric modeling.

The analysis of HiRes-II monocular data was similar to that for HiRes-I. With the greater elevation coverage at HiRes-II, it was feasible to reconstruct the shower geometry from timing alone. With the geometry of the shower known, we calculated the light profile and fit it to the Gaisser-Hillas parameterization[9].

For both HiRes-I and HiRes-II events, the photo-electron count was converted to a shower size at each atmospheric depth, using the known geometry of the shower, and corrected for atmospheric attenuation. We integrated the resulting function over x (using the determined values of N_m and x_m) and then multiplied by the average energy loss per particle to give the visible shower energy. A correction for energy carried off by non-observable particles to give the total shower energy ($\sim 10\%$)[15] was then applied.

3. Flux

We calculated the cosmic ray flux for HiRes-I above 3×10^{18} eV, and for HiRes-II above 2×10^{17} eV. This combined spectrum is shown in Fig. 1., where the flux $J(E)$ has been multiplied by E^3. The data sample for HiRes-II includes only dates between December 1, 1999 and May 4, 2000. A larger data sample will be shown at the conference. The error bars represent the 68% confidence interval for the Poisson fluctuations in the number of events. The HiRes-I flux is the result of two completely independent analyses[1, 18], which yielded essentially identical flux values. The most recent spectrum from the AGASA experiment[6] is also shown.

The largest systematic uncertainties are the absolute calibration of the photo-tubes ($\pm 10\%$)[5], the yield of the fluorescence process ($\pm 10\%$)[12], the correction for unobserved energy in the shower ($\pm 5\%$)[15, 14], and the modeling of the atmosphere[4].

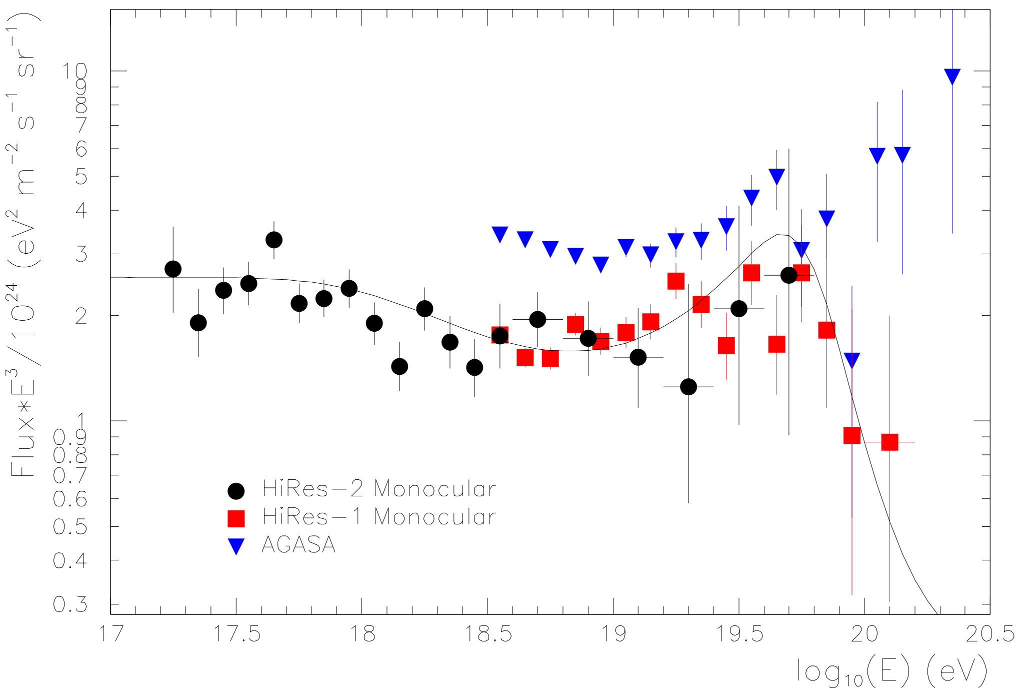

Fig. 1. The two HiRes monocular spectra, along with the AGASA spectra. A fit to the HiRes spectra to a two component model is also shown

Our spectrum contains two events which reconstruct with energies greater than 10^{20} eV, measured at $1.0\times$ and 1.5×10^{20} eV. The fitted geometries were insensitive to variations in aerosol parameters. Assuming a purely molecular atmosphere ($\tau_A = 0.0$), we obtain a lower energy limits of $0.9\times$ and 1.2×10^{20} eV.

In the energy range where both detectors' data have good statistical power, the results agree with each other very well. The data are consistent with previous experiments which observed the second knee at about $10^{17.6}$ eV, and the ankle at about $10^{18.6}$ eV[7].

A power law fit to our data from the ankle to the pion production threshhold (from $\log E$ of 18.7 to 19.8) yields an index of -2.82 ± 0.06. The AGASA results suggest that this power law should continue unchanged above the pion threshhold. But our three data points above 19.8 are not consistent with that interpretation (26.2 events are predicted where only 10 are observed, a Poisson probability of 2.8×10^{-4}).

Our data are consistent with the GZK cutoff. As an example of what one would expect, we have fit the data to a model that consists of galactic and extra-galactic sources[16], that includes the GZK cutoff. We use the extra-galactic source model of Berezinsky *et al.*[8], where we assume that protons come from sources distributed uniformly across the universe with a maximum energy at the source of 10^{21} eV, and an assumed galactic spectrum consistent with observations that the composition changes from heavy to light near 10^{18} eV. The χ^2 of this fit is 40.5 for 32 degrees of freedom, and the fit is shown in Fig. 1.. Details can be found in [3]. In this model the peak at $\log E$ of 19.8 is due to the pion production threshold, and the second knee comes from e^+e^- production threshold.

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