Stereoscopic Measurement of the Flux of Ultra High Energy Cosmic Rays by the High Resolution Fly's Eye

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Abstract. **The High Resolution Fly's Eye (HiRes) experiment has measured the flux of ultra high energy cosmic rays using the stereoscopic air fluorescence technique. The HiRes experiment consists of two detectors that observe cosmic ray air showers via the fluorescence light they emit. HiRes data can be analyzed in monocular mode, where each detector is treated separately, or in stereoscopic mode where they are considered together. Using the monocular mode, the HiRes collaboration measured the cosmic ray spectrum and made the first observation of the Greisen-Zatsepin-Kuz'min (GZK) cutoff. The cosmic ray spectrum measured by the stereoscopic technique is presented here. Good agreement is found with the monocular spectrum in all respects.**

Keywords: **Ultra High Energy Cosmic Rays (UHECR), HiRes, stereo spectrum**

I. INTRODUCTION

The spectrum of ultra high energy cosmic rays ($E \geq 10^{18}$ eV) is important to understanding several long outstanding problems in astrophysics. The sources which are capable of accelerating particles to such enormous energies have not yet been identified and the acceleration mechanisms are not yet understood. The distance to UHECR sources is theorized to be limited to < 50 Mpc during e^+e^- pair production and pion production due to interactions with the primordial CMB radiation. This energy loss mechanism will cause a sharp drop in the cosmic ray flux at $E \approx 10^{19.7}$ eV (called the GZK cutoff), yet several experiments have observed cosmic rays in excess of 10^{20} eV. Features of the spectrum such as the knee, the second knee, the ankle, and the GZK cutoff will help solve these questions concerning astrophysical sources of UHECRs.

II. THE HiRes EXPERIMENT

The High Resolution Fly's Eye (HiRes) is an air fluorescence detector located on the U.S. Army Dugway Proving Ground, about 100 km southwest of Salt Lake City, Utah. This site was selected for its good atmospheric conditions and dark night skies. HiRes is comprised of two detector sites, HiRes1 and HiRes2, which each utilize multiple telescopes consisting of a large mirror with an effective area of about 3.8 m^2, focused onto a cluster of 256 photomultiplier tubes. Each tube views about 1° of sky. Light is collected by the telescopes and the PMT charge and time distributions are digitized and stored for later analysis.

HiRes1 consists of 21 telescopes arranged in a single ring configuration covering 336° in azimuth and 3° to 17° in elevation. Sample and hold electronics are utilized such that the pulse height and timing information of each pixel triggered in an event is stored for analysis. HiRes1 collected data from May 1997 to April 2006.

HiRes2 consists of 42 telescopes arranged in a double ring configuration, each ring covering about 352° in azimuth. Ring 1 mirrors view from 3° to 17° in elevation and ring 2 mirrors view from 17° to 31°. HiRes2 employs an FADC electronics system which samples the pulse height and timing information of each pixel every 100 ns. The HiRes2 detector is located 12.6 km southwest of HiRes1. HiRes2 collected data from December 1999 to April 2006.

Each detector can independently collect data from UHECR induced extended air showers, also called monocular mode. Monocular spectrum measurements from HiRes1 and HiRes2 can be found in [1] and [2]. Events which are viewed by both detectors are said to be collected in stereo mode. HiRes monocular spectrum measurements are superior to stereo measurements in that they can provide better statistical power due to longer running time and coincidence between detectors is not needed. The energy range of the spectrum can also be extended in the case of HiRes2, since it can see higher elevation angles, thereby allowing the shower maximum of low energy showers to be observed.

On the other hand, stereo measurements have much better geometry resolution than monocular measurements, which translates to better energy resolution. Energy resolution scales proportionally with the resolution of distance determination to the shower. By combining the geometric information of the shower from two independent detectors, the shower's direction and distance to each detector can be constrained, thereby reducing uncertainties in atmospheric corrections that must be

made when converting PMT charge profile to light emitted by the shower. The energy resolution of HiRes1 and HiRes2 operating in monocular mode is about 23% and 17% respectively over their entire energy ranges, whereas the stereo energy resolution is 12% over all energies.

Stereo event measurement also allows for two independent measurements of a shower's energy, depth of shower maximum ($x_{\max}$), and the size of the shower at shower maximum ($N_{\max}$). This cross checking is an additional constraint on the reconstruction of showers to ensure only well reconstructed events are used in the data analysis.

III. Reconstruction Method

HiRes is an air fluorescence detector. When an UHECR particle interacts with an air molecule in the upper atmosphere, an Extended Air Shower (EAS) is produced. π^0 produced in the inelastic collision, quickly decay to 2 γ. These photons pair produce e^+e^-, which then undergo bremsstrahlung producing more photons, and the cycle repeats. Most of the energy of the shower is converted to this electromagnetic component which excite N_2 molecules which emit light in the UV range (300 nm - 400 nm) upon deexcitation. Some of this UV light is transmitted towards the large mirrors at HiRes, which reflect the light through a UV bandpass filter, onto a cluster of PMTs.

A shower appears as a line source to our detectors. Using the surveyed geometry of the detector elements, a shower-detector plane can be determined by an amplitude weighted fit to the PMT charge distribution. For a monocular reconstruction, the timing of the shower must be employed to determine the shower direction and distance from the detector. For stereo reconstruction, the intersection of the two shower detector planes defines a line which is the shower track as shown in figure 1. This method of using two detectors gives HiRes about $0.5°$ resolution in shower pointing direction, compared to $> 5°$ for monocular reconstruction. The geometry of the shower is then known, including the distance to the shower, as well as the shower direction.

The light profile of the shower is then collected into bins measured in $N_{pe}/m^2/degree$ which describe the light flux arriving on the PMT cluster. Bins are constructed by summing the light from one or more tubes and corrected for cluster acceptance by ray tracing to correct for PMT cluster obscuration and inactive regions of the cluster. At HiRes1, the binning is performed by considering only the geometry of the shower and the cluster. This method is called angular binning. At HiRes2, the rapid FADC sampling of the shower allows for time bins to be constructed, providing a finer profile of the shower.

Using the light profile and the geometry of the shower, a fit to a Gaussian-in-age shower profile is done. The
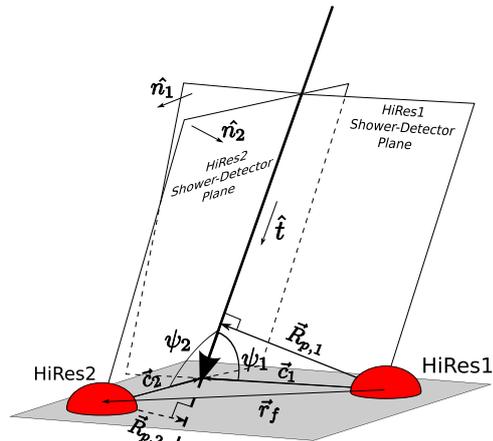

Fig. 1. Using the stereo geometry of two crossed planes to locate the shower track.

Gaussian-in-age profile is written as

$$N_e(s) = N_{\max} \exp\left(-\frac{1}{2}\left(\frac{s-1}{\sigma_s}\right)^2\right) \qquad (1)$$

where $N_e(s)$ is the number of charged particles in the shower at age s, $N_{\max}$ is the number of charged particles at shower maximum, and σ_s is the shower width parameter. The shower age is related to the atmospheric slant depth, x, by

$$s(x) = \frac{3x}{x + 2x_{\max}} \qquad (2)$$

where $x_{\max}$ is the depth of shower maximum. This shower profile can be integrated to determine the energy of the primary particle which initiated the EAS. This calorimetric energy can be written as

$$E_{cal} = \alpha \int_0^\infty N_e(x)dx \qquad (3)$$

where α is the average energy loss of electrons in air found through CORSIKA simulations and has the value of 2.4 MeV/g/cm^2. An additional correction is made for EAS energy that does not contribute to the electromagnetic component of the shower (hadronic interactions and muon and neutrino production) which we can not directly measure. This correction is less than 10% for showers with primary energy greater than 10^{18} eV.

Figure 2 shows the shower profile of an EAS as seen by both detectors. It can be seen that the earliest point of the shower seen by HiRes1 is deeper in the atmosphere than HiRes2. This is typical since HiRes1 does not cover high elevation angles. The energy of this event is about 8.5 EeV. The energy of the shower can be checked by independent shower profile integration at both sites using equation 3 as a crosscheck.

Calibration of the HiRes detector is done using a stable xenon flash bulb acting as the standard candle. This light source is shone on all mirrors periodically and the photometric response of each phototube is measured. During each night of operation, a stable YAG laser light
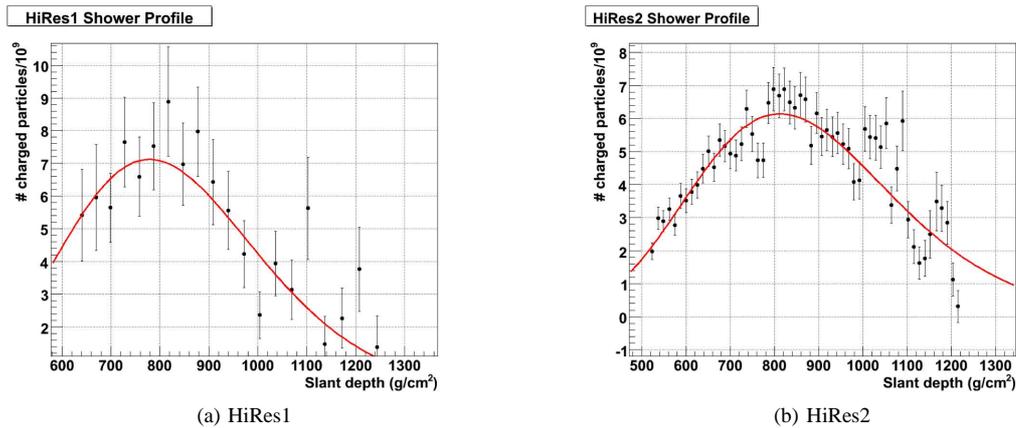
(a) HiRes1

(b) HiRes2

Fig. 2. Profile of a stereo reconstructed event. The number of shower particles as a function of slant depth as observed by each detector is shown, as well as the fit to the profiles. The energy of this event was found to be 8.59 ± 0.62 EeV at HiRes1 and 8.43 ± 0.18 EeV at HiRes2.
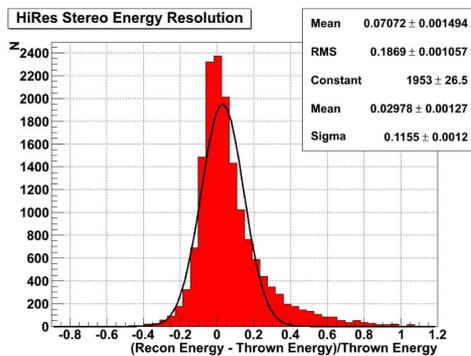

Fig. 3. The energy resolution of the stereo reconstruction over all energies ($E > 10^{18.2}$ eV).
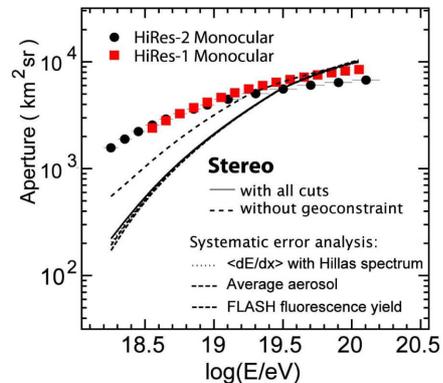

Fig. 4. The HiRes stereo aperture and comparison to the monocular apertures.

source is fired upon the mirrors, fed via optical fibers, and the nightly PMT response is determined. Nightly fluctuations in PMT response are calculated for each night of operations and are used to determine the gain relative to the standard candle. In this way, each PMT's gain is measured for every night and corrected for in the reconstruction. Further details can be found in [3].

Since the atmosphere is our calorimeter, as well as the transmission medium, we must also understand the conditions of the atmosphere. Steerable YAG lasers are employed which probe the air around the detectors to measure the aerosol content in a bistatic lidar configuration, where each detector can act as the light receiver. Efforts to understand and correct for the atmosphere can be found in [4] and [5].

Monte Carlo simulations of the detector are used to determine our agreement with data and to measure reconstruction efficiency. We have good overall agreement between data and Monte Carlo for all relevant observables. The energy resolution is measured to be 12% as shown in figure 3.

IV. STEREO SPECTRUM

The aperture, which is a measure of the detector's acceptance, is not known *a priori*. We rely upon our

Monte Carlo to accurately simulate the operating conditions of our detector and throw events uniformly throughout the range of distances and directions in which our detector is sensitive to cosmic ray air showers. Our injection spectrum goes as E^{-3} and we measure the reconstruction efficiency of our analysis program and calculate the aperture. Figure 4 shows the stereo aperture and comparisons to the monocular apertures as well. The stereo aperture reaches 10,000 km^2 sr at the highest energies. It drops below the monocular apertures due to a shrinking region of acceptance, since both detectors must trigger on these events and they can only be seen effectively in the region between the two detectors. Figure 4 also shows the effect of subjecting the aperture calculation to different systematic effects which are important for good energy resolution. The lower set of lines show that when aerosol, dE/dx, and fluorescence yield are varied, the systematic effect is negligible when a fully efficient aperture is used.

The fully efficient aperture is constructed by limiting event acceptance by imposing a constraint on the maximum distance to showers. Only showers within a certain radius of the centroid of the two detectors are included in the aperture calculation. As showers are viewed
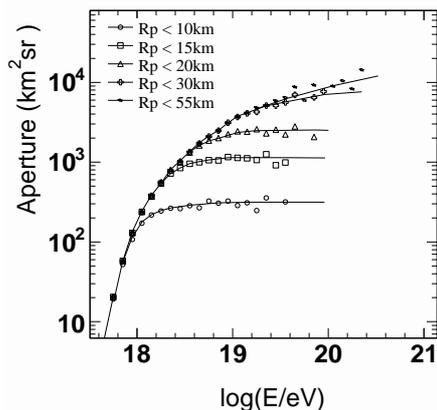
Fig. 5.   The fully efficient aperture shows that by restricting event selection to those within a given radius of the detector, all events above a certain energy are reconstructed with 100% efficiency.
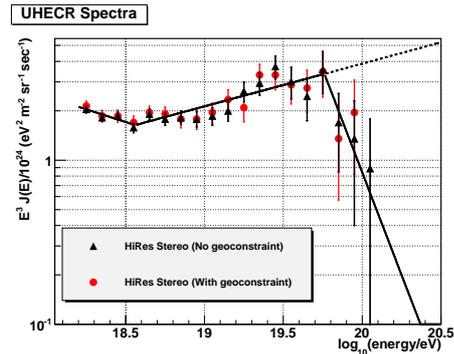

Fig. 6.   The HiRes stereo normal and fully efficient spectra. The fit to the normal spectrum is shown. The dashed line shows the shape of the spectrum assuming a single power law fit above the ankle.

at further distances their reconstruction efficiency is reduced due to less light reaching the detectors. As figure 5 shows, if we restrict our acceptance of events to those that fall within 10 km of our detectors, the reconstruction efficiency is 100% for those showers with energies greater than $10^{18.2}$ eV.

The stereo spectrum calculated using the "normal" and the fully efficient apertures is shown in figure 6. This is a plot of $E^3 J(E)$ to enhance the spectral features. The results of the two spectra calculations are similar. The normal spectrum has 2267 events, while the fully efficient spectrum has only 1147 events. A fit to the spectrum which allows for 2 break points where the spectral index changes, fits the data very well with χ^2/DOF of 14.6/15. The ankle is found to be at 18.65 ± 0.05 log(E/eV) and the GZK cutoff at 19.75 ± 0.04 log(E/eV). The spectral indices are found to -3.31 ± 0.11 below the ankle, -2.74 ± 0.05 between the ankle and the GZK cutoff, and -5.5 ± 1.8 above the GZK cutoff. This is in excellent agreement with the monocular spectrum measurement claiming the first observation of the GZK cutoff [6]. For the fully efficient spectrum, if a single power law were expected above the ankle, 27 events are expected, whereas we only observed 7. The cumulative Poisson probability for this is 5.2×10^{-6}, which corresponds to 4.4 σ. The main systematic effects related to stereo energy reconstruction are uncertainties in the photometric scale (10%), fluorescence yield (6%), dE/dx (10%), and atmospheric aerosol corrections (6%). Added in quadrature, the total systematic uncertainty is 17%, corresponding to a uncertainty of 30% in the flux calculation.

V. Conclusions

The energy spectrum of ultra high energy cosmic rays has been measured using the HiRes detector in stereoscopic mode. With an energy resolution of 12%, the stereoscopic energy measurement is superior to monocular measurements in this regard, although the monocular measurement provides greater statistical power and a wider energy range. The stereo spectrum agrees well with the monocular measurement observing spectral breaks at the ankle and the GZK cutoff. Further details of the stereo spectrum measurement can be found at [7].

VI. Acknowledgements

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