Air Fluorescence Calorimetry with the High Resolution Fly's Eye and Telescope Array Experiments

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Abstract. The air fluorescence technique was first successfully deployed on the Fly's Eye Experiment (1981-1993) by the University of Utah. Its successor, the High Resolution Fly's Eye (HiRes) experiment has further exploited this technique, first in hybrid mode with the MIA muon array (1993-1996), and then in monocular and stereoscopic modes (1997-2006). Results from HiRes will be presented, including evidence for the Greisen-Zatsepin-K'uzmin (GZK) Effect predicted 40 years ago. Most recently, members of the HiRes are collaborating with groups from Japan, led by University of Tokyo, to construct and operate the Telescope Array (TA) experiment, which will deploy a large scintillation-based ground array in combination with fluorescence detectors. Funding for TA in the US has already been approved by NSF. TA will begin operation in 2007.

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INTRODUCTION

The High Resolution Fly's Eye (HiRes) Experiment consists of two air fluorescence detectors located on the U.S. Army Dugway Proving Ground in the West Desert of Utah. The project is a collaboration between University of Utah, Columbia University, Rutgers University, University of New Mexico, University of Montana,the Los Alamos National Laboratory (LANL), University of Tokyo, and the Institute for High Energy Physics (IHEP) in Beijing, China. The two detector sites are placed 12.6 km apart. The HiRes-1 site, in operation since 1997, sits atop Little Granite Mountain and comprises 22 mirrors covering $3^\circ - 17^\circ$ in elevation. The HiRes-2 site began routine observations at the end of 1999. It consists of 42 mirrors which view elevation angles in the range $3^\circ - 31^\circ$.

Each of the two detectors serve as sampling calorimeters, using the Earth's atmosphere as the scintillation medium. As in the case of the original Fly's Eye experiment [1], the mirrors collect and focus the UV (*fluorescence*) light emitted by nitrogen molecules in the wake of the charged particles in the extensive air shower. Photomultiplier tubes (PMTs) are placed as pixel elements at the focal plane of the ~ 2 m diameter, spherical mirrors. In this way, HiRes, like Fly's Eye, images the longitudinal development of air showers. Unlike the original Fly's Eye experiment, full-sky coverage is not needed because HiRes detectors are able to detect showers up to 40 km away, whereas the scale height of the atmosphere itself is only about 8 km.

During 1993-1996, a group of 14 prototype mirror units were operated in a "tower" configuration, with the five highest mirrors pointing up to 70° in elevation. The tower

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had a limited azimuth ($\sim 30^\circ$) in its field of view, which is centered on the MIA muon array located ~ 3.5 km away. This combination of detectors represented the World's first hybrid (fluorescence + ground array) detector system, preceding the AUGER experiment by more than a decade. The composition results from the HiRes-MIA combination are included later along with those of HiRes.

Each HiRes mirror units uses the same basic optical design. Accounting for obscuration by the PMT cluster, each mirror has an effective collection area of 3.72 m^2. Each mirror is instrumented with a 16×16 array of PMTs in a hexagonal close-packed cluster. Each PMT pixel covers a 1° cone in the sky. Each mirror unit thus covers about 16° in azimuth, and about 14° in elevation angle. The 1° pixel size gives HiRes a factor of five improvement in resolution. Since air showers are approximately linear, this five-fold improvement results in a corresponding five-fold increase in the signal-to-noise ratio for the individual pixels. The increase in sensitivity gives HiRes an order-of-magnitude improvement in the aperture over that of the Fly's Eye. Additional details of the detectors components and readout electronics can be found elsewhere [2, 3]). The HiRes experiment ceased routine observation in April of 2006.

HIRES RESULTS

Energy Spectrum

The HiRes experiment was designed to measure the energy spectrum, composition, and anisotropy of ultrahigh energy cosmic rays above 10^{18} eV. The combined monocular spectrum (from HiRes-1 and HiRes-2 monocular measurements) was first published in 2004 [4]. We show here a recent spectrum (As of June 2006) in Figure 1, along with the stereo spectrum reported by the Fly's Eye [5] and the HiRes-MIA hybrid detector [6]. This spectrum clearly shows two spectral features expected from attenuation from the cosmic microwave background: (a) the GZK suppression (from photo-pion production) [7] near $10^{19.8}$ eV and the associated *pile-up* just below, and (b) the ankle structure at $10^{18.5}$ eV. The latter is consistent with previous measurement shown.

Composition and Cross-Section Measurements

The depth of shower maximum (X_{MAX}) from the HiRes stereo data was used in a composition study of UHE cosmic rays above 10^{18} eV. The stereoscopic observation of HiRes offers the advantage of redundancy. The difference between the measurements from the two sites can be used to check the accuracy of the Monte Carlo simulations, especially in its ability to model the detector resolutions. Figure 2 shows the relative difference between the X_{MAX} values measured from HiRes-1 and HiRes-2 detectors, shown for both data (left) and Monte Carlo (right). The vertical axes in these graphs are in log scale. The two histograms have the same width. This excellent agreement serves to validate the X_{MAX} resolution of ~ 30 g/cm^2 obtained from simulations [8].

The average X_{MAX} vs. energy, as measured by HiRes, has been published [8]. These are shown, with the measurements at lower energies from the HiRes/MIA hybrid, in

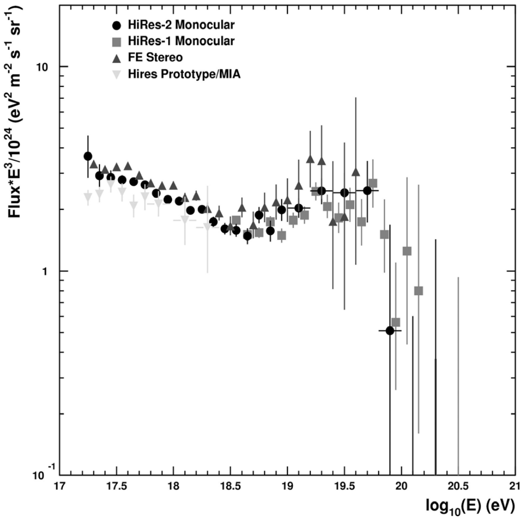

FIGURE 1. The HiRes monocular spectrum (6/2006) plotted with the Fly's Eye stereo [5] and HiRes/MIA [6] spectra. The HiRes measurement shows clearly an ankle structure at $10^{18.5}$ eV consistent with previous measurements, and a suppression at $10^{19.8}$ eV consistent with the GZK Effect [7].

Figure 3. Also included are model predictions for proton and iron. The HiRes results, which spans the energy range of $10^{18.0} - 10^{19.3}$ eV, are consistent with an apparently constant, and predominantly light composition. The elongation rate, $dX_{MAX}/d\log E$, roughly parallel to the model lines, is also indicative of constant composition. In contrast, the HiRes/MIA results show a transition from predominantly heavy composition at $\sim 10^{17}$ eV to a predominantly light one by 10^{18} eV.

Next, the stereo data has also been analyzed to extract the proton-air cross-section by fitting the slope of the exponential tail of the X_{MAX} distribution for values greater than 700 g/cm^2. This analysis uses a reverse Monte-Carlo deconvolution to fit for the exponential slope, λ_{p-air}, of the distribution of the interaction depth of the primary cosmic rays in the atmosphere. The result of the de-convolution fit applied to the HiRes stereo data (up to Jan. 2004) is shown in Figure 4. From a fitted value of $\lambda_{p-air} =$ 52.7 cm^2/g, a cross-section of 456 ± 17(stat.)$+39$(sys.)-11(sys.) mb was obtained for $E = 10^{18.5}$ eV. Details of this analysis can be found elsewhere [9].

The proton-air cross-section was translated to a proton-proton cross-section [10] and this result is shown in Figure 5. The figure also shows accelerator-based pp data selected by M. Block and fitted to a parametric model [10]. The extrapolation of this model gives a prediction that lies within the error bars of the HiRes result. The figure also shows the results from the Fly's Eye experiment and the old Akeno Array, renormalized with a k-factor of 1.32 obtained from CORSIKA simulations (using both QGSJet and Sybill) [10].

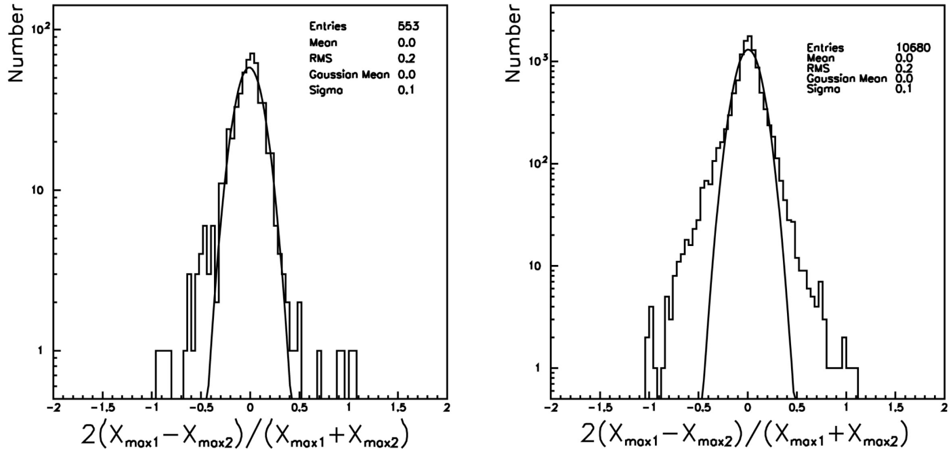

FIGURE 2. Histograms of the relative difference between the X_{MAX} values measured from HiRes-1 and HiRes-2 detectors, shown for data (left) and Monte Carlo (right).

Anisotropy

Several studies have been performed to search for both small and large-scale anisotropy using the HiRes-1 monocular data. These have yielded null results. They include searches for point-sources [11] and cross-correlation with the AGASA doublets and triplet [12, 13]. Null results were also obtained in a search for dipole enhancements in the direction the Galactic Center, Centaurus A, and M87 [14]. In particular, HiRes did not observe any small-scale clustering such as that reported by AGASA [15, 16].

Anisotropy studies were also performed on the HiRes stereo data, which has better than 0.6° angular resolution. One study showed the stereo events above 10^{19} eV to be consistent with isotropy at all small angular scales [17]. A search for coincidence with AGASA doublets and triplets did find one event in coincidence with the AGASA triplet. However, a Monte Carlo study of 10,000 isotropic datasets with yielded 47 sets which gave the same coincidence with equal or greater statistical significance. This is consistent with a $\sim 2.5\sigma$ fluctuation. Moreover, the chance probability of $\sim 5 \times 10^{-3}$ does not take into consideration the penalty associated with the *a posteriori* AGASA cuts, which would further weaken the significance of the observed coincidence.

An apparent correlation between HiRes stereo events and BL-Lacertae (BL-Lac) objects was first noted by Gorbunov *et al.* [18]. Using a binned analysis, the authors compared the positions of HiRes stereo events above 10^{19} eV extracted from previous HiRes publications to those of the 156 “BL" objects in the Veron Catalog [19], and found 11 events to lie within 0.8° of a “BL" object, with a chance probability estimated at $\sim 10^{-3}$. An independent analysis by the HiRes group using an unbinned maximum-likelihood method reproduced the apparent correlation with a chance probability of $\sim 10^{-4}$.

The HiRes BL-Lac correlation has been published [20] with data up to January of

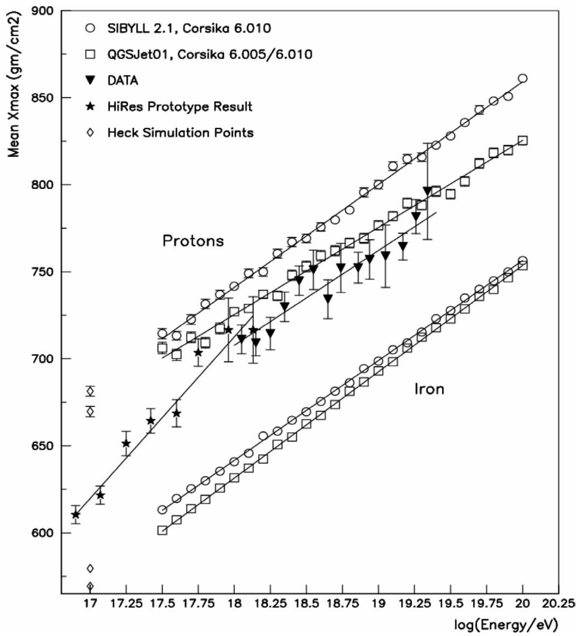

FIGURE 3. Average measured X_{MAX} for UHE cosmic rays plotted as a function of energy for both HiRes stereo data [8] and for the HiRes/MIA hybrid [6].

2004. An illustration of this correlation is shown in Figure 6, which plots the the number of pairs of HiRes events and known BL-Lac objects as a function of θ, their angle of separation. They are histogrammed in one degree angular bins and the pairs weighted by $1/\sin(\theta)$ to remove the sharp rise from zero of ordinary phase-space. We note that this plot was not used for the actual statistical analysis in the publication. A peculiar feature of this observation is that the correlation is consistent with the HiRes stereo angular resolution.

TELESCOPE ARRAY

Currently, a new hybrid experiment is under construction in Millard County, Utah. This new project is a Japan-U.S. collaboration that will deploy a ground array of 576 plastic scintillation counters in a rectangular grid of 1.2 km spacing. Three new fluorescence detectors will initially be deployed at the periphery of the ground array. Each of these stations will provide a field of view of $3^\circ - 17^\circ$ in elevation and 108° in azimuth, which is sufficient to provide full coverage of the ground array at energies above 10^{19} eV, which is about 8 times the size of AGASA.

The existing 64 HiRes mirror units will be redeployed at two additional sites inside the ground array at ~ 6 km from two of the new TA fluorescence stations. These new stereo pairs will extend stereo fluorescence coverage down to $\sim 10^{17.5}$ eV in order to

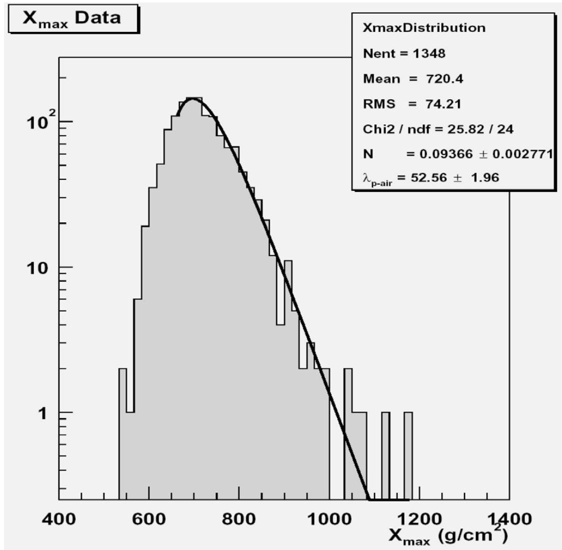

FIGURE 4. Histogram showing the measured X_{MAX} distribution and the result of the de-convolution fit to the exponential tail. A value of $\lambda_{p-air} = 52.7$ cm^2/g was obtained, which corresponds to a proton-air cross-section of 456 ± 17(stat.)$+39$(sys.)-11(sys.) mb.

provide a reliable stereo measurement of the energy spectrum over the ankle region. In addition, this configuration of detectors will also extend hybrid stereo coverage (where each event is measured by at least two fluorescence detectors and the ground array) over the entire ground array for energies above 10^{19} eV. In stereo-hybrid mode, the angular resolution will approach $\sim 0.1^\circ$. This attribute will make TA an extremely powerful cosmic ray anisotropy detector.

TA will also construct 15 additional detector units with 3 m diameter mirrors. These will be placed at one of the 6 km sites overlooking an infill ground array. With elevation coverage comparable to the original HiRes prototype tower, larger mirrors, and broader azimuthal coverage, the new tower detector will overlap with the stereo TA measurements and extend it down to $10^{16.5}$ eV.

The construction and deployment of TA detector elements are well under way. The ground array and the peripheral fluorescence sites will be completed in the spring of 2007. The TA project has also received funding support in the U.S. from the National Science Foundation (NSF). The interior fluorescence detectors and infill array should begin construction in early 2008.

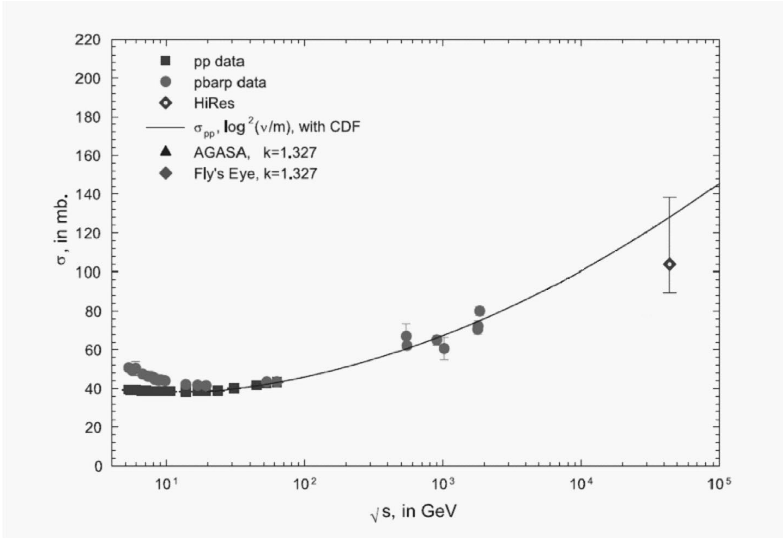

FIGURE 5. The HiRes proton-air inelastic cross section converted to a proton-proton cross-section [10]. The HiRes data point is shown with an extrapolation of lower-energy pp data [10], which gives a prediction that lies within the error bars of the HiRes result. Also shown are the Fly's Eye and Akeno results re-normalized using a k factor of 1.32 obtained from CORSIKA simulations (with QGSJet and Sybill) [10].

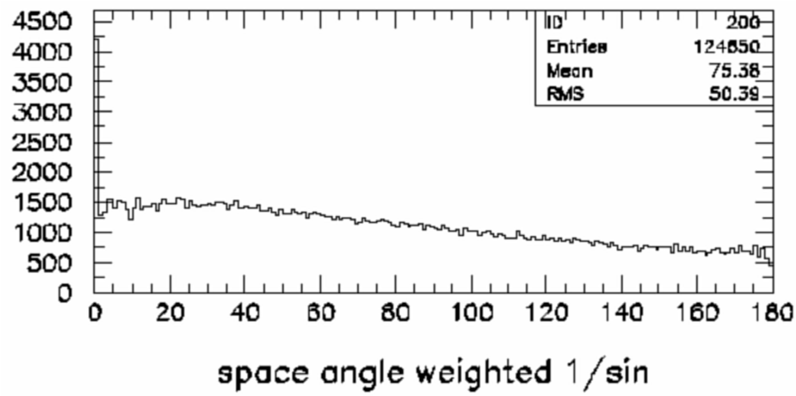

FIGURE 6. The number of pairs of HiRes events and known BL-Lac objects as a function of θ, their angle of separation. They are histogrammed in one degree angular bins and the pairs weighted by $1/\sin(\theta)$ to remove the sharp rise from zero of ordinary phase-space. We note that this plot was not used for the actual statistical analysis in the HiRes publication

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