The View From HiRes

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Abstract. The status and results from the HiRes atmospheric fluorescence experiment are discussed. In particular, results on composition from the HiRes Prototype and CASA/MIA hybrid experiment and preliminary results from the HiRes monocular data on the highest energy cosmic rays are presented. Evidence for the cosmic ray spectrum continuing past the Greisen-Zatsepin-Kuzmin cutoff is evaluated and the impact of stereo data on this question is discussed

INTRODUCTION

Penzias and Wilson's unexpected discovery of the universal microwave background in 1965 is now the centerpiece of our understanding of the evolution of the universe and the Big Bang scenario[1]. It also has deep implications for our understanding of the origins of the highest energy cosmic rays. In 1966, Greisen realized that ultrahigh energy cosmic ray protons would be affected by interactions with this radiation. Greisen predicted that, if cosmic ray sources were distant enough from us and if their flux extended past 10^{20} eV (100 EeV), then they would interact inelastically with the black body radiation[2]. This interaction has a threshold given by the onset for single pion photoproduction. He predicted that a smooth power law spectrum of cosmic rays would be cut off by this onset of inelastic interactions near 60 EeV if sources were uniformly distributed throughout the universe. This effect was independently predicted by Zatsepin and Kuzmin. The search for this so-called Greisen-Zatsepin-Kuzmin 'GZK' cut-off has been one of the primary goals of ultra-high-energy (UHE) cosmic ray physicists ever since. The lack of observation of a cut-off could imply that UHE cosmic ray sources are relatively close to us, on the order of 50 Mpc or less. If that is the case, then significant anisotropies towards the source directions should be observed. Of course, the degree of anisotropy depends on the magnitude of extragalactic magnetic fields and the composition of the cosmic rays themselves. Neveretheless, if local AGN's are the sources, then one would expect that the highest energy cosmic rays will align in their directions.

The Fly's Eye and the AGASA experiments observed events in 1991 and 1993 respectively that appear to be clearly beyond the predicted cut-off. Since then, significant additional data from AGASA and from the new High Resolution Fly's Eye (HiRes) experiment have become available and appear to confirm the original findings. No significant astronomical alignments of these events with nearby astrophysical objects has been found. This has stimulated a great deal of interest and all kinds of hypotheses ranging from decays of topological defects to violation of special relativity have been proposed. Much more data is needed to clarify the situation. In this talk, I will discuss the results from the original Fly's Eye and the Hires/CASA/MIA hybrid prototype and present preliminary results from the HiRes monocular data. HiRes stereo data is just becoming available. At this point, it is primarily useful in checking the monocular reconstruction and Monte Carlo energy resolution results but will be critical in determining the composition of cosmic rays at the highest energies.

The Atmospheric Fluorescence Technique

The atmospheric fluorescence technique as we presently understand it was developed by G. Cassiday, E. Loh, and colleagues at the University of Utah, based on a prototype detector built by K. Greisen at Cornell University[3]. The longitudinal development of the EAS in the atmosphere is measured directly by this technique. As charged particles in an EAS cross the atmosphere, they excite nitrogen fluorescence. Unlike Cherenkov radiation, this UV light is isotropic and hence EAS can be viewed from all directions by appropriate detectors. The fluorescent photon yield is about four photons per meter per ionizing particle and is approximately independent of altitude (up to 10 km). The light is emitted in several bands from 300 to 400 nm. The atmosphere has negligible absorption and has a horizontal scattering length of 10 to 15 km at these wavelengths. A single Fly's Eye detector subdivides the hemisphere of the sky into pixels defined by photomultiplier tube apertures. As a shower develops through the atmosphere, a pixel whose field of view intersects the shower position will detect signals whose amplitude, after correction for geometrical and atmospheric effects, are proportional to the number of ionizing particles passing through that part of the atmosphere. The moving shower defines a "track" through the atmosphere which in turn results in a "track" of pixels in the detector. The integral of the reconstructed shower profile is directly proportional to the primary energy. The method is essentially calorimetric, measuring the total energy deposition in the atmosphere by means of the amount of fluorescence produced. This technique does not require a complex Monte Carlo calculation to determine the energy scale. Instead, the energy scale is given by the N_2 fluorescence efficiency for ionizing particles which has been measured by a number of groups [4].

The University of Utah group built the first Fly's Eye in 1982. A second partial eye, called Fly's Eye II was built 3.5 km from the first eye in 1985. An EAS can then be detected by both eyes simultaneously. This stereo data set had much more precision and redundancy than the monocular eye measurements. The Fly's Eye experiment took data from 1982 to 1992. While the instantaneous aperture of a fluorescence detector is very large (about about 1000 km^2str for the monocular Fly's Eye and 400 km^2str for the stereo case) the effective on time of fluorescence detectors is limited to approximately ten percent by the requirement of dark nights and good weather.

Results From the Fly's Eye Experiment

Stereo and Monocular Results on the Cosmic Ray Spectrum

The Fly's Eye data[5] is divided into poorer resolution monocular data and better resolution but lower statistical significance stereo data. The Fly's Eye stereo spectrum exhibits significant structure (at the 5 sigma level of statistical significance) between 1 and 10 EeV (see Fig 1). Of particular interest is a steepening near 3 x 10^{17}, now dubbed the "second knee", to which we will return later.

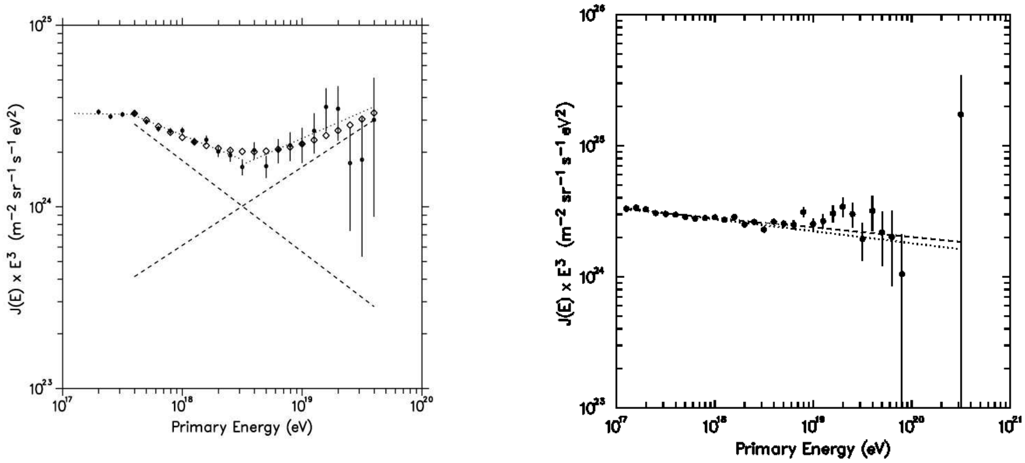

FIGURE 1. The Fly's Eye spectrum. Left hand figure is the stereo spectrum. The data is shown as solid dots. Dashed lines indicate hypothetical two component spectrum whose sum is indicated by the dotted line. Right hand figure is the monocular spectrum. The data is shown as solid dots. The dashed line is the best single power law fit to the whole spectrum. The dotted line is the best fit to the data below 10^{19} eV.

The monocular Fly's Eye data has significantly greater statistics than the stereo data. Although a flattening of the spectral index is evident above 10 EeV, the pronounced dip structure near 3 EeV observed in the stereo data is absent. The discrepancy arises because the monocular data has poorer energy resolution. If the monocular energy resolution is used with the stereo spectrum, the spectrum obtained is consistent with the observed monocular data.

While the Fly's Eye monocular spectrum generally conforms to expectations for a GZK cutoff (a pile-up of events below the cut-off would generate the observed flattening of the spectrum just below60 EeV), a single exceptional event was observed with energy well beyond it. This event with an estimated energy of 320 EeV was detected on October 15, 1991. In all respects, this event appears to be well reconstructed and its longitudinal shower profile is shown in Figure 2. The position of shower maximum in the atmosphere for the best fit at 13 km is consistent with expectations for either a proton or heavy nucleus induced shower.

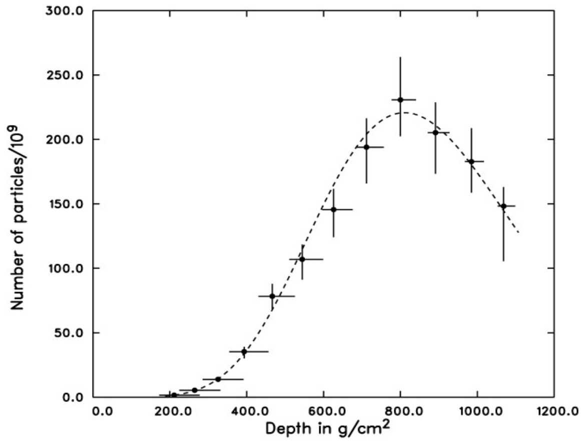

FIGURE 2. The longitudinal profile of the highest energy event observed by the monocular Fly's Eye. Vertical error bars are dominated by photostatistics. Note the horizontal error bars are correlated since the depth of shower in the atmosphere is completely determined by the overall geometry of the event.

Composition of Cosmic Rays from 10^{17} to 10^{19} eV

Indirect information on cosmic ray composition can be extracted from the distribution of EAS shower maxima in the atmosphere. Heavy nuclei such as iron will interact higher in the atmosphere with an interaction length of 15 gm/cm^2 and their shower maxima are expected to be near 600 gm/cm^2 at .1 EeV. Proton primaries will interact with a mean free path near 70 gm/cm^2 and have shower maxima near 700 gm/cm^2 and larger shower by shower fluctuations in atmospheric depth. The average depth of shower maximum increases logarithmically with primary energy . The slope of the average shower X_{max} versus primary energy plot is called the elongation rate. Different nuclei are expected to have similar elongation rates but have different intercepts on an X_{max} versus energy plot. It is possible to look for consistency with a light, predominantly protonic composition, or a heavy composition composed of CNO and Fe group nuclei. In particular, data can be compared to the two extreme possibilities of a pure proton and a pure Fe CR flux. Expected elongation rates for individual nuclei are 50 to 55 gm/cm^2 per decade of energy and are very insensitive to the details of hadronic interaction models. A cosmic ray flux that changes from a predominantly heavy to a light composition would be reflected in a measured elongation rate larger than expected for a constant composition. Figure 3 shows the stereo Fly's Eye data and the expected positions of X_{max} for Fe and p incident particles. It is apparent that the composition appears to be getting lighter in the decade between 1 and 10 EeV. The change from a heavy to a light composition occurs in the same energy interval where significant change in the spectral slope is observed. A straightforward interpretation of this is the appearance of a light, hard spectrum extragalactic cosmic ray flux which begins to dominate over the heavy softer galactic component

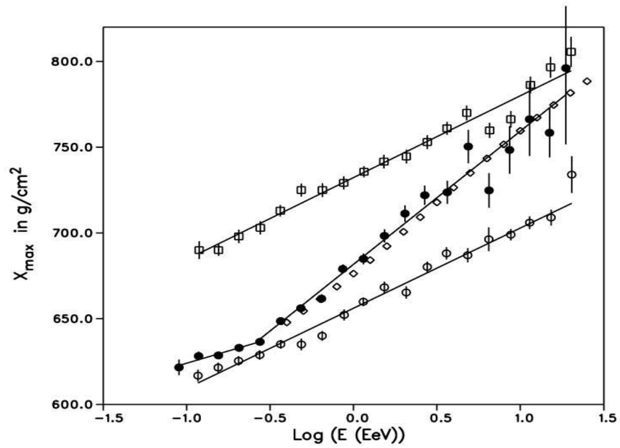

FIGURE 3. The stereo Fly's Eye elongation rate. Average shower maximum is shown in solid circles. Open circles indicate predictions for a pure iron flux while open boxes represent a pure proton flux. Open diamonds correspond to predictions of the two component power law model show in Fig. 1.

THE HIGH RESOLUTION FLY'S EYE DETECTOR

The High Resolution Fly's Eye Detector (HiRes)[6] is a collaboration between the University of Adelaide, Columbia University, the University of New Mexico, Rutgers, Montana State University, the University of Tokyo, and the University of Utah. This experiment will increase sensitivity to cosmic rays above 100 EeV by at least an order of magnitude with respect to the Fly's Eye results. It is designed to study the cosmic ray energy flux above 3 EeV and measure its composition and anisotropy with significantly improved resolution. Construction was completed in the summer of 1999. The two sites, the original Fly's Eye I site (now called HiRes I) and a new HiRes II site are 12.5 km distant. The HiRes detector gets its increased aperture and improved resolution through decreasing the pixel size from 5.5 degrees by 5.5 degrees (the tube aperture of the Fly's Eye detector) to one degree by one degree and by increasing the mirror area from 1.7 to 3.5 m^2. The resultant increased signal to noise ratio makes showers at 30 km impact parameter distance easy to detect. The improved sampling along the track allows even short tracks to be well reconstructed. In addition, all events will be seen in stereo so that the measurement will always be overconstrained. One major advantage of this approach is that events will have two independent measurements of their energy and longitudinal shower profile. This makes it possible to measure the detector resolution function in X_{max} and energy directly from the data. Knowledge of this resolution function is critical in making sure that an apparently continuing spectrum is not due to spill down effect produced by the detector resolution. At the highest energies, the aperture is 13,000 km^{2}str.

Results from the HiRes Prototype

An earlier prototype version of the HiRes experiment ran for three years overlooking the CASA/MIA muon and electron ground array detectors[7] 3.5 km away. In this experiment, cosmic ray EAS were detected in both the fluorescence and ground array modes simultaneously. The energy range is restricted to .1 to 1 EeV by the size of the ground array. Results confirm that the elongation rate is inconsistent with a constant composition and is in agreement with a gradual change from a heavy to a light composition (see Figure 4). The muon number density at 600 m as a function of energy is also measured. While the predictions for a pure Fe composition are somewhat below the measured muon densities, indicating a possible problem with the hadronic model, the slope of this energy dependence is consistent with a change from a heavy to a light composition (see Figure 5). As in the case of the Xmax elongation rate, the slope of the muon densitiy versus energy plot is more reliably predicted than the absolute magnitude of the density. The shape of the cosmic ray spectrum measured in this hybrid experiment is shown if Figure 6. While statistics are limited, this higher resolution data shows the beginning of the same “second knee” structure seen in the earlier Fly’s Eye experiment. Fig. 6 also shows the combined results of a number of experiments from below the first “knee” to 1 EeV. There is significant evidence that the “second knee” represents a spectral index change (.3) very similar to the first.

The same data set can be used to derive the average shower profile for energies near .1 EeV. In this case, individual showers are normalized to same energy and X_{max} position in the atmosphere, converted to shower size versus shower age, and averaged. The results, shown in Fig. 7 show excellent agreement with the Gaisser-Hillas parametrization. Fluctuations about the mean are consistent with photostatistics.

Preliminary Monocular HiRes Results

HiRes I was completed in 1997 and has been accumulating data since then. Events seen by only one detector can be reconstructed by fitting to the distribution of time of arrival of light at each phototube. This monocular timing fit only works well for tracks approaching 20^o in projected angular length. Because HiRes I has a limited vertical field of view ($2\text{-}17^o$ above the horizon) most events are significantly shorter. Monte Carlo studies show that the width of EAS showers in the atmosphere, expressed in gm/cm^2 is quite constant, independent of energy, composition or model. This has been confirmed by the HiRes prototype studies discussed above. To improve resolution we do a combined fit to the timing and to the central value of the predicted shower width. Monte Carlo studies show that the resolution improves as the energy increases with small non-gaussian tails. We expect a 20% energy resolution near 100 EeV. The monocular aperture of HiRes I is very similar to the stereo aperture and approaches 10,000 km^2str near 100 EeV.

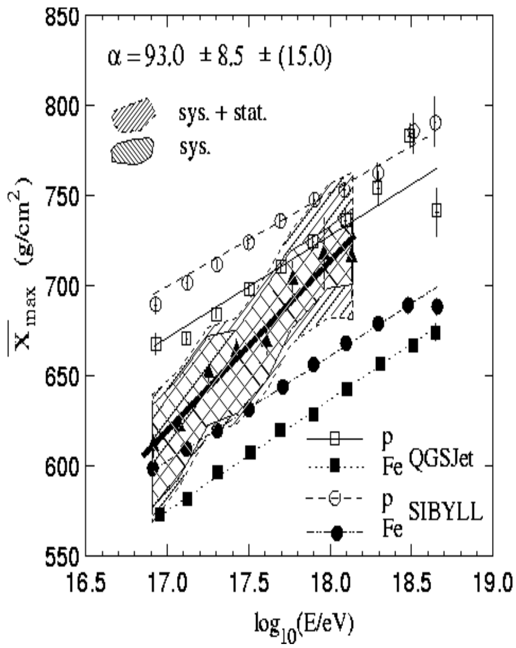

FIGURE 4. HiRes Prototype/MIA elongation rate. Dark solid line and cross hatched area indicate the central value of the data and systematic unertainty bounds. Lines and open and closed circles and squares indicate predictions for pure proton and pure Fe flux using two different hadronic models.

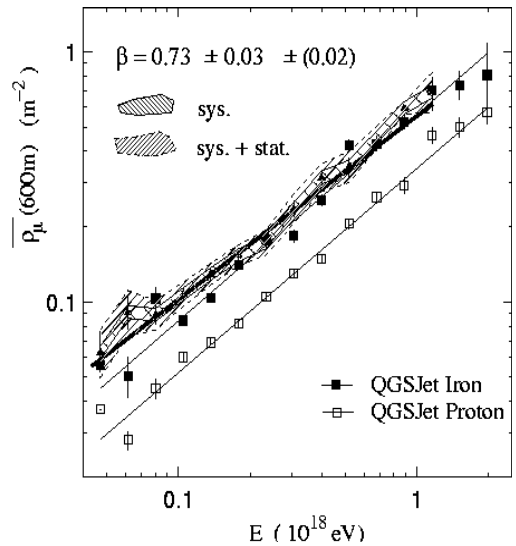

FIGURE 5. HiRes Prototype/MIA muon density at 600m as a funtion of energy. Dark solid line and cross hatched area indicate the central value of the data and systematic uncertainty bounds. Solid squares are predictions for pure Iron. Open squares are predictions for pure protons. Both predictions assume the QGSJet hadronic model. Note that theoretical predictions underestimate the number of muons.

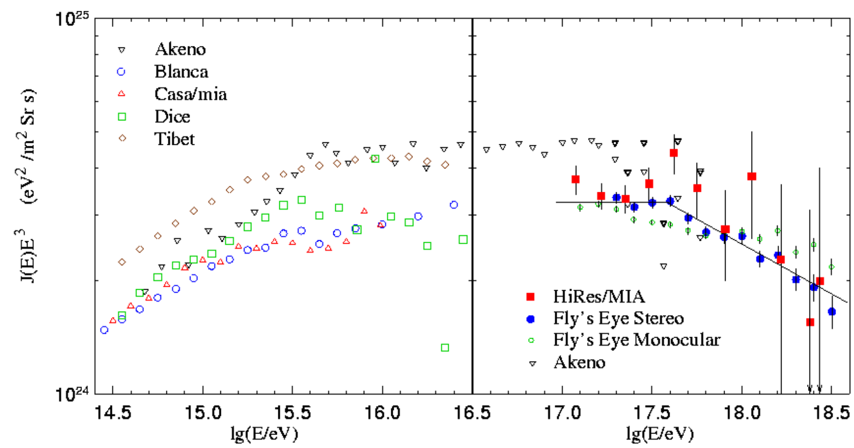

FIGURE 6. Combined world data on the cosmic ray spectrum from below the "knee" to the "second knee". Note magnitude of spectral beak for "second knee" is similar to the first "knee" of the specrum

Preliminary results on the spectrum are shown in Figure 8. The solid line is a fit to the original stereo Fly's Eye spectrum, smoothly extrapolated to the highest energies. The data indicates a number of events nominally above 100 EeV. This data is analyzed using a standard desert atmospheric model and does not yet have corrections for the night to night variation in the atmospheric transmission. It is clear, however, that systematic atmospheric effects will not cause all of the events to move below 100 EeV. In particular, the highest energy event with an energy of 270 EeV, observed at an impact parameter of 30 km, would have its energy shifted down to 140 EeV if the atmosphere became as clear as it possibly could be - i.e. if it was a pure molecular atmosphere for that night. This is still significantly above the universal GZK prediction of 60 EeV.

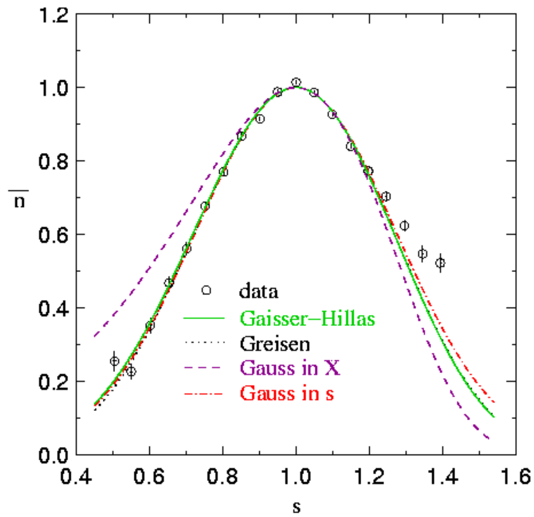

FIGURE 7. Average shower profile measure by the HiRes prototype. The Gaisser-Hillas function is an excellent representation of the data. Deviations of the last few data points are due to systematic effects and are not significant.

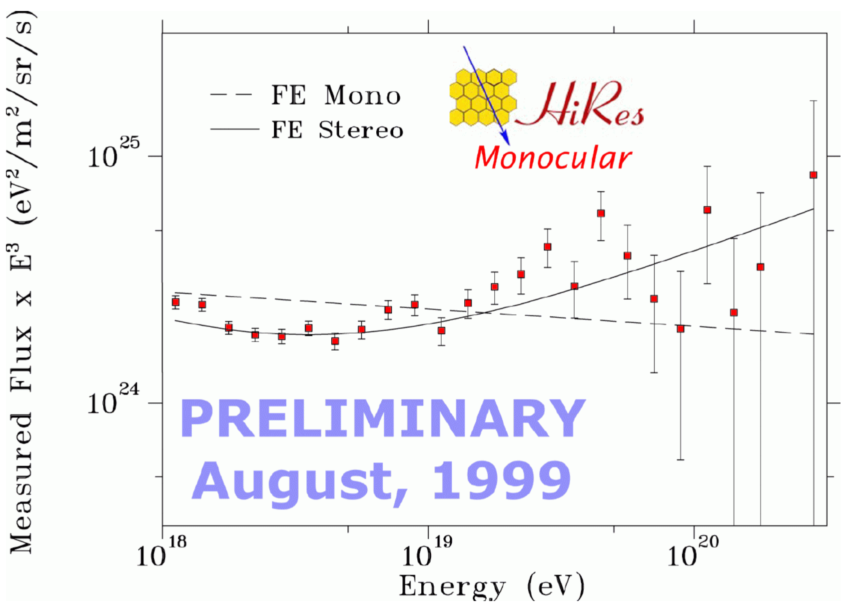

FIGURE 8. Preliminary results from the HiRes I monocular data. Solid line indicates flux extrapolated from Fly's Eye stereo spectrum. Dashed line indicates flux extrapolated from fit to Fly's Eye monocular data.

Several hundred stereo events have now been reconstructed. These events can be used to test the monocular reconstruction method. At least below 10^{19} eV where sufficient statistics exists, results indicate that the monocular energy resolution is about 25%, quite consistent with Monte Carlo calculations. It is also clear that the trend towards improving resolution with energy predicted by the Monte Carlo is occurring in the data. As more stereo statistics are accumulated, the question of non-gaussian tails on the resolution function can be addressed in more detail. However, there is no evidence from the current data that these tails or larger than those exhibited by the Monte Carlo.

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