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Observation of the GZK cutoff by the HiRes Experiment

Pierre Sokolsky [a], for the HiRes Collaboration

[a]Physics Department, University of Utah, 115 S 1400 E, Salt Lake City, Utah 84112

Results from the High Resolution Fly's Eye (HiRes) on the observation of the Greissen-Zatsepin-Kuzmin cutoff in the cosmic ray spectrum are presented. We observe a cutoff consistent with the GZK predictions with a five sigma significance. The nature of the cosmic ray composition near the GZK cutoff is also discussed as well as possible correlations of the highest energy cosmic rays with AGNs in the Northern sky.

1. Introduction

Over the last forty years a variety of experiments have studied the cosmic ray spectrum at extreme energies. While it appears at first to be a simple power law, it has been known for some time that this spectrum exhibits significant structure which must reflect the cosmic ray origins and propagation (see Fig 1). Above energies of 10^{14} eV, the spectrum departs from an $E^{-2.7}$ power law and steepens with a break at 10^{15} eV known as the "knee". A second "knee" near 3×10^{17} eV has also been reported by a number of experiments. Above that we see an "ankle" structure with a dip near $3 - 5 \times 10^{18}$ eV. All this structure was predicted to culminate in a cutoff near 6×10^{19} eV beyond which the spectrum drops abruptly. This final cutoff was predicted in 1966 by K. Greissen, G. Zatsepin and V. Kuzmin [1] as a result of the inelastic interaction of protons with the 2.7 degree black body radiation. Protons with energies above 6×10^{19} eV could interact inelastically with the black body photons, producing pions and secondary hadrons each with lower energies. Integrated over all possible sources in the universe, this would produce a well-defined break, dubbed the GZK cutoff.

In point of fact, as seen in Fig.2, the GZK mechanism will produce a fractionation of distance to source and energy of protons from that source [2]. A broad secondary minimum near 3×10^{18} eV develops because of e^+e^- production of protons on the black body radiation which causes an additional energy loss. Because of this dependence on distance, the extragalactic cosmic ray spectrum shape carries information about galactic evolution as measured by cosmic ray luminosity.

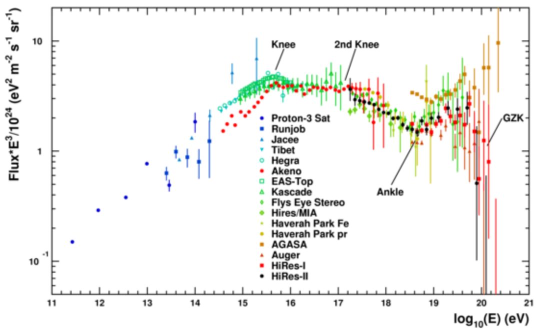

Figure 1. The cosmic ray spectrum multiplied by E^3 to accentuate structure in this steeply falling spectrum.

The existence of the GZK cutoff has been controversial as many initial attempts to detect this spectral feature did not find it. Indeed many of the pioneering ground array experiments such as Volcano Ranch, Haverah Park and AGASA seemed to see a continuing flux of particles beyond the GZK energy [3]. The Yakutsk array was the sole exception. The Fly's Eye air fluorescence experiments measured a spectrum consistent with the GZK cutoff with the exception of one extraor-

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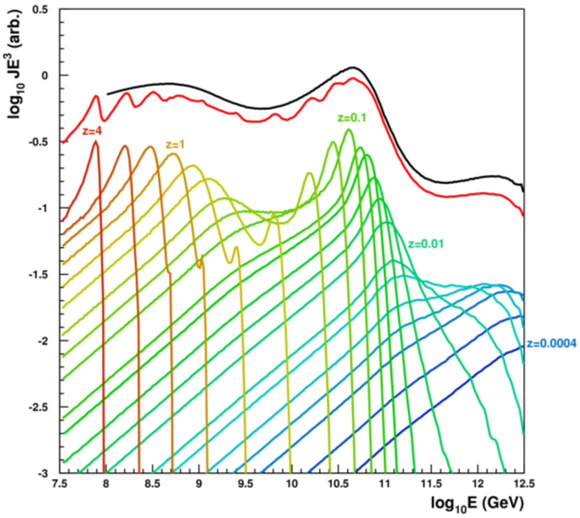

Figure 2. Contribution to the total extragalactic cosmic ray spectrum of sources at different redshifts z.

dinarily energetic event at 3×10^{20} eV [4] which attracted a great deal of attention. This was followed by AGASA claiming to see up to ten more such post-GZK events [5]. Only nearby sources (closer than about 50 Mpc) could produce protons which would escape the GZK mechanism, due to lack of interaction length. However, none of the post-GZK events pointed to any known active galaxy in our neighborhood. Many exotic theoretical ideas were proposed to explain this apparent "paradox" [6].

The High Resolution Fly's Eye (HiRes) [7] in the state of Utah has produced data which now clearly shows the existence of a termination in the cosmic ray flux consistent with the GZK cutoff prediction. This measurement uses a pure air fluorescence technique. This observation has been recently confirmed by the Pierre Auger Observatory (PAO) in Argentina which uses a combined ground array and air fluorescence detector [8].

2. The HiRes experiment

The HiRes experiment consists of two sites (HiRes I and II) 12.6 km apart, located at Dugway proving Ground in Utah. Each site consists of telescope units (22 at HiRes I and 42 at HiRes II) pointing at different parts of the sky. The detectors observe the full 360 degrees in azimuth but cover from 3 to 16.5 (Hires I) and from 3 to 30 degrees (HiRes II) in elevation angles. Since most cosmic ray events in this energy range are detected at distances of between 5 and 30 km from the detectors, higher elevation angles contribute little to the event rate. Each telescope consists of a 3.72 m^2 effective area mirror and a 256 phototube camera cluster in the mirror focal plane. The phototubes subtend a one degree by one degree field of view on the sky. The tubes view signals through a UV filter which cuts out light below 300 nm and above 400 nm (corresponding to the air-fluorescence spectral range). The instantaneous aperture of the HiRes detector approaches 10000 km^2sr at 1020 eV but is limited by a 10 percent on time due to the requirement of dark, clear, moonless nights. The arrival direction of the cosmic ray initiating the shower can be reconstructed monocularly, using the triggered tube pointing directions to determine the shower-detector plane, and the relative tube triggering times to determine the impact parameter and angle of the track within the plane. From this information, the impact parameter, zenith and azimuth angles can be easily calculated. Stereo reconstruction affords much better precision. If the shower is detected by both HiRes I and II and two shower-detector planes are determined for the event, the shower direction must lie along the intersection of the two planes. Because of the simplicity of the method, it is virtually impossible to get the shower direction and distance systematically wrong, once the pointing directions for the phototubes are accurately determined.The largest data sample consists of events seen by HiRes I only, since this detector turned on three years before the completion of Hires II. Because of the limited elevation angle coverage of HiRes I monocular events are too short in angular spread for reliable determina-

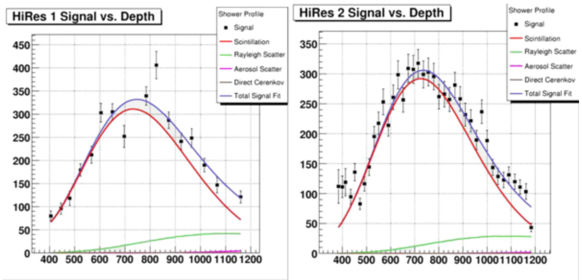

Figure 3. Stereo cosmic ray profiles of an event measured by the eyes of the HiRes Stereo detector.

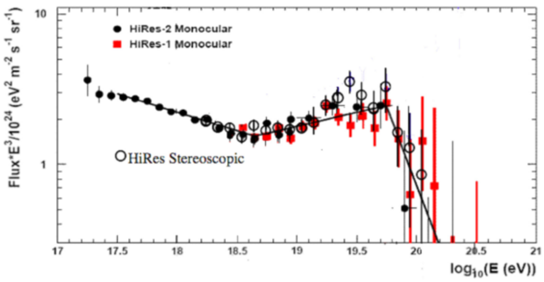

Figure 4. The cosmic ray spectrum multiplied by E^3 as determined by the HiRes monocular and stereo analysis.

tion of the geometry by timing alone. Experiment and simulation have shown that while the position of an EAS in the atmosphere will fluctuate, its shape has very little variation. This shape is well described by the Gaisser-Hillas function. To improve resolution for the HiRes I data, the expected form of the shower development (i.e. the shape of its longitudinal profile) is used to constrain the time fit. The HiRes II event sample has longer track lengths and the geometry can be well determined from timing alone. The profile constrained HiRes I fit has been carefully checked using both simulations and comparisons of reconstruction with stereo data for the subset of events where HiRes II was also triggered. Once the geometry of the event is determined, the tube signals are used to determine the shower size in one degree angular bins on the sky (for HiRes I), or in time bins corresponding to the FADC clock at HiRes II. Finally, combining the bin signal, corrected for atmospheric attenuation, with knowledge of the shower geometry, the size of the shower as a function of atmospheric depth is calculated. Cherenkov light scattered into the detector is subtracted in an iterative process. The depth of shower maximum, X_{max}, and shower energy E are determined from the Gaisser-Hillas fit to the profile. The shower energy is proportional to the integral of the Gaisser-Hillas function after corrections are made for missing energy due to neutral particles or high-energy muons hitting the earth's surface. The missing energy correction (10 percent) is weakly hadronic model dependent. Fig. 3 shows a typical stereo event profile.

3. Results on the Ultra-high Energy Cosmic Ray Spectrum

Fig. 4 shows the HiRes monocular and stereo spectra which clearly show the "ankle" structure and a cutoff at the expected GZK energy [9]. Fig 5. Shows the result of fitting the monocular spectrum (which has the highest statistics) to three power laws with floating break points. The statistical strength of the monocular observation of the GZK cutoff is about 5 sigma. The stereo spectrum, while more limited in statistics has the best energy resolution due to the simplicity and robustness of the geometrical reconstruction. In addition, we have developed a series of cuts which make the stereo aperture essentially insensitive to variations in atmospheric transparency and other systematic errors.

The detector aperture is defined as the effective area times solid angle in which an air shower of a given energy will trigger the detector. For each of the HiRes detectors, the aperture grows with energy since higher energy showers are brighter and can be detected at larger distances. The aper-

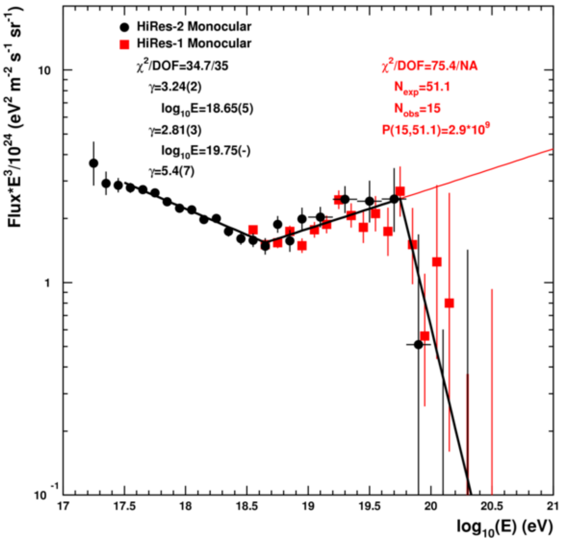

Figure 5. The cosmic ray spectrum multiplied by E^3 for the HiRes monocular data together with the result of a fit to three power laws with floating break points.

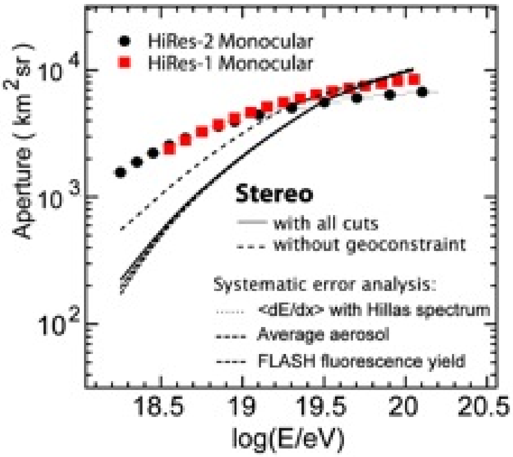

Figure 6. The HiRes detector aperture for monocular and stereo data. The stereo apertures shown correspond to the total and geometricaly restricted apertures as described in the text.

tures saturate at the highest energies to a value approaching 10,000 km^{2}sr. The apertures are calculated using a detailed detector and shower Monte Carlo whose results are carefully compared with measured event distributions. The stereo aperture is determined by demanding that both detectors trigger on the same event. The apertures are shown in Fig. 6. The stereo aperture has a similar form to the monocular aperture but it drops significantly below the monocular apertures for energies below $10^{18.5}$.

Our calculation of the stereo aperture can be made more robust by imposing additional constraints. Simulations show that within a constant distance between our detectors and showers we collect cosmic ray events with near 100 percent efficiency above a certain energy. For instance, if the impact parameter Rp is less than 10 km, all events above $10^{18.2}$ eV are collected with nearly 100 percent efficiency while for 20 km the corresponding energy is 10^{19} eV. This information can be read from Fig. 7. This defines a geometrical aperture constraint which allows us to calculate the aperture and spectrum at all energies with excellent efficiency that is largely unaffected by atmospheric conditions.

The stereo spectrum in Fig. 4 shows an ankle structure in agreement with the monocular spectra. A broken power law fit to the ankle region as determined from the stereo spectrum yields power law indexes of -3.31 $\pm$ 0.11 and 2.74 $\pm$ 0.05 below and above the minimum at $10^{18.56}$ respectively. This is to be compared with the results from the monocular spectrum of -3.25 $\pm$ 0.01 and -2.81 $\pm$ 0.03 and a minimum at $10^{18.65}$. The GZK suppression break point is at $10^{19.76}$ eV for the stereo spectrum and at $10^{19.75}$ for the mono spectrum.

Fig. 8 shows the PAO combined spectrum [10]. The spectrum is qualitatively similar to the HiRes spectrum with a clear GZK cutoff whose statistical significance is approximately six standard deviations.

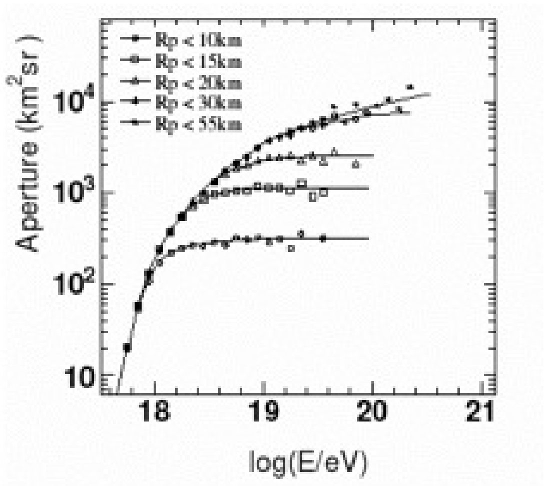

Figure 7. Hires stereo aperture as a function of energy for events falling within geometrical Rp cuts.

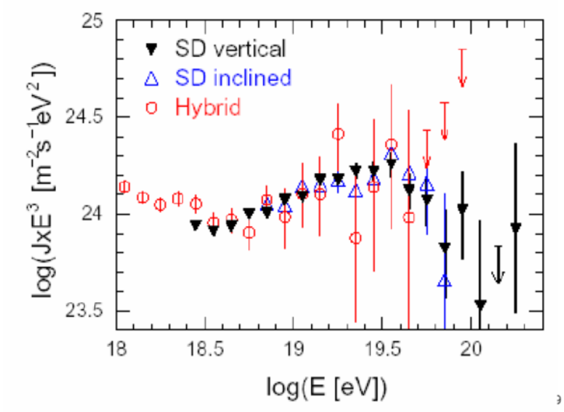

Figure 8. The cosmic ray spectrum multiplied by E^3 as measured by the PAO surface array calibrated with air fluorescence data. Data below 3×10^{18} eV comes from hybrid events.

4. Correlation of Arrival Directions with AGNs

Since cosmic rays just below the GZK cutoff must come from relatively close-by sources (z less than 0.2 or so (see Fig. 2)) the HiRes data has been examined for correlation with various galactic catalogues. The PAO experiment in the Southern Hemisphere has found a possible correlation with AGNs in the Veron catalogue with z less than 0.18 and with cosmic ray energies above $10^{19.75}$ [11]. The correlations manifest as an excess of events within five degrees of the direction of the AGNs relative to that expected from a random correlation. This correlation was looked for and the search parameters tuned in the first year of PAO data taking. The second year data, which corresponds to an independent data sample, was then examined using these predetermined conditions and a three sigma excess correlation with these AGNs was found. While not yet statistically very strong, the correlation is intriguing, though it is not clear if the AGN's are tracking a structure, rather than being sources themselves. Another possibility is that what is being detected is a broad enhancement from Cen A, which is a very close-in galaxy only visible in the South.

The HiRes collaboration has used the PAO parameters to search for an excess in the Northern hemisphere and has found nothing beyond that expected from random coincidences. This is approximately the same number of events as the independent sample used by PAO [12]. An independent scan of half of the HiRes data yielded the most significant signal with slightly different cuts in z and angle from PAO, but with a significantly lower minimum energy. However, applying these cuts to the other half of the HiRes data yielded no significant correlation (see Fig. 9). Several more years of PAO data will triple the statistics and should clearly determine whether this correlation is real in the South. In the North, we await first results from the Telescope Array detector, which is just beginning to take data. Several years of operation should double the available data in this energy range in the North.

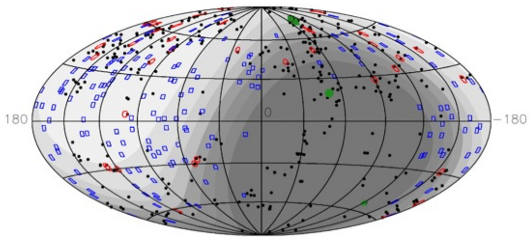

Figure 9. Correlations between the highest energy HiRes events (cuts described in the text) with AGNs from the Veron catalogue.

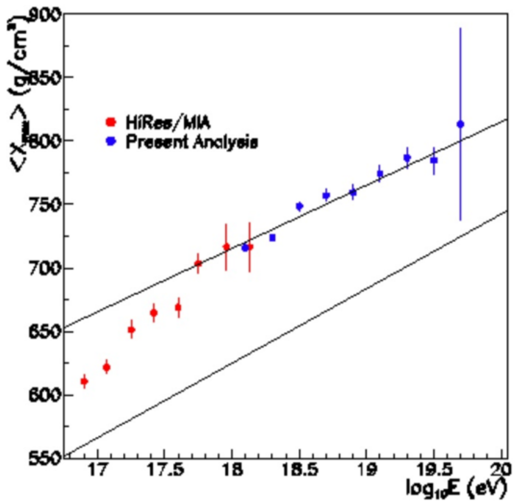

Figure 10. Cosmic ray elongation rate as measured by the HiRes/MIA, HiRes Stereo together with predictions for proton and Fe primaries using the QGSJet model.

5. Cosmic Ray Composition

Can we conclude that after more than forty years, the GZK cutoff has at last been discovered? The independent five sigma observations by HiRes and PAO of the required flux downturn at the predicted energy would seem to indicate that this is the case. However, the GZK effect is based on the cosmic ray flux being composed of protons. A heavy composition, mostly composed of Fe nuclei for example, could exhibit structure due to nuclear fragmentation. At sufficiently large distances, an initially heavy flux would turn into a light composition dominated by protons. More close in sources would, however, still contribute their share of heavy nuclei. Has the universe assembled a distribution of sources and a heavy composition at the source to somehow mimic the GZK like structure seen by experiments? One way to answer this question is to attempt to measure the composition as a function of energy. The distribution of shower maxima (X_{max}) is known to be sensitive to the composition of cosmic rays. Both the elongation rate and the absolute position of the mean X_{max} and its fluctuations about the mean carry information about the primary composition [13]. While the detailed interpretation is hadronic model dependent, a measure of the systematic uncertainties can be garnered by comparing the predictions of a variety of hadronic models, from QGS-Jet and Sybbil to DPM jet [14]. The elongation rate, or slope of the mean Xmax per decade of energy, is essentially model independent up to energies of 30 to 50 EeV and the variation in absolute mean X_{max} position are in agreement to within 25-30 gm cm^{-2} in this energy region. Since the separation between a pure Fe and a pure p spectrum is about 70-100 gm cm^{-2}, qualitative information about the nature of the primary particles can certainly be obtained using this technique. Fig. 10 shows the elongation rate from the HiRes stereo data [15]. Also included in this figure are lower energy data from an earlier hybrid HiRes/MIA experiment [16]. Above 1 EeV, the data is consistent with a light, mainly protonic composition. A similar result has been presented by the PAO collaboration [17]. Here "hybrid" events are used, as PAO has limited stereo aperture at lower energies. Given that the quoted systematic errors for both experiments are about 15 gm cm^{-2} for the mean value of X_{max}, the data are in reasonable agreement. The apparent change of slope of the elongation rate below 10^{18} eV may indicate the transition to a heavier galactic composition and would place the termination of the galactic cosmic ray spectrum in this energy region, near the "second knee" of the spectrum. There is still controversy about the amount of heavy nuclei that can be accommodated near the GZK energy, but it is already clear that a dominantly heavy Fe flux can be ruled out. In fact, the HiRes data is quite consistent with a purely protonic spectrum above a few times 10^{18} eV.

Acknowledgments

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