

# Fitting the HiRes Data

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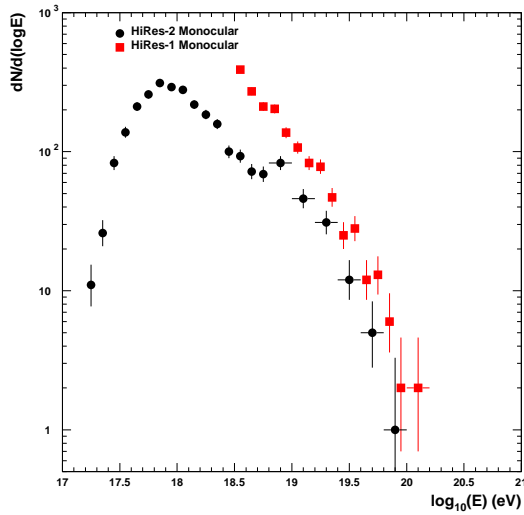
**Abstract.** We fit the recently released monocular spectra of the High Resolution Fly's Eye (HiRes) experiment with broken power laws to identify features in the ultra-high energy cosmic ray (UHECR) spectrum. These fits find the previously observed feature known as the Ankle at  $10^{18.5}$  eV, as well as evidence for a suppression at higher energies, above  $10^{19.8}$  eV. We use the integral spectrum along with the  $E_{1/2}$  test to identify this high energy suppression with the GZK suppression. Finally, we use a model of uniformly distributed extragalactic proton sources together with a phenomenological model of the galactic cosmic ray spectrum to compare the HiRes spectra to what should be expected from the GZK suppression, and to measure how the extragalactic sources must evolve and what the input spectral slope must be to fit the HiRes data.

## 1. Broken Power Law Fits

The HiRes Collaboration has recently released two measurements of the UHECR flux using monocular observations from its two sites[?]. We will first describe broken power law fits made to these measurements. These fits can be used to identify features and to estimate their statistical significance.

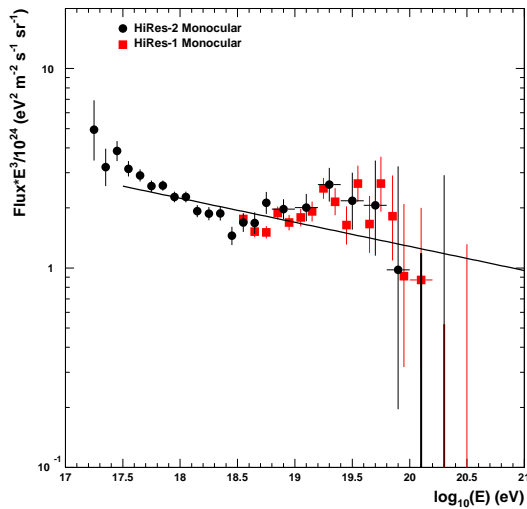
All the fits presented in this paper were performed using the normalized binned maximum likelihood method[?]. This method requires comparing the numbers of events expected in a given model to the number actually observed. The number of expected events is obtained from the predicted flux divided by the same exposure used to calculate the observed flux. The numbers of events observed by HiRes are shown in Figure ???. The binned maximum likelihood method also allows one to use bins in which there were no observed events, but in which events were expected. The result of the fits are expressed in terms of a quality-of-fit parameter  $\chi^2$  which approaches a true  $\chi^2$  in the limit of large numbers of events.

The broken power law fits are only to bins above  $10^{17.5}$  eV. While HiRes-II does have three bins below this energy, these bins have poor statistics. We don't fit these bins in order to avoid biases due to an expected change in the spectral slope, the Second Knee, at about this energy.

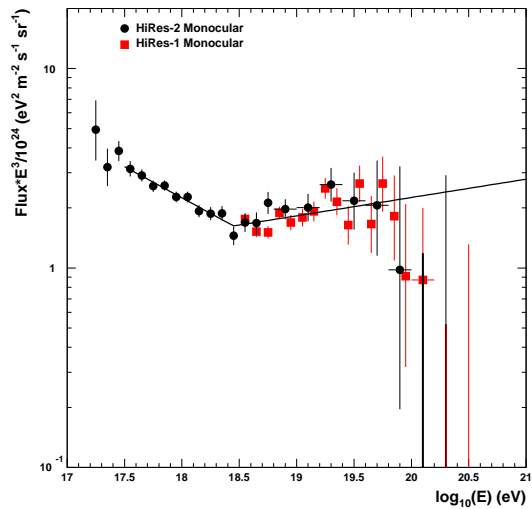


**Figure 1.** The numbers of events in each bin of the HiRes monocular spectrum measurements[?]. The HiRes-I measurement includes two empty bins centered at 20.3 and 20.5. The HiRes-II measurement includes two empty bins centered at 20.1 and 20.3

Fits of the HiRes monocular spectra to a broken power law,  $J(E) = CE^{-\gamma}$ , with zero, one and two floating break points are shown in Figures ??-??. The parameters of these fits are given in Table ??.

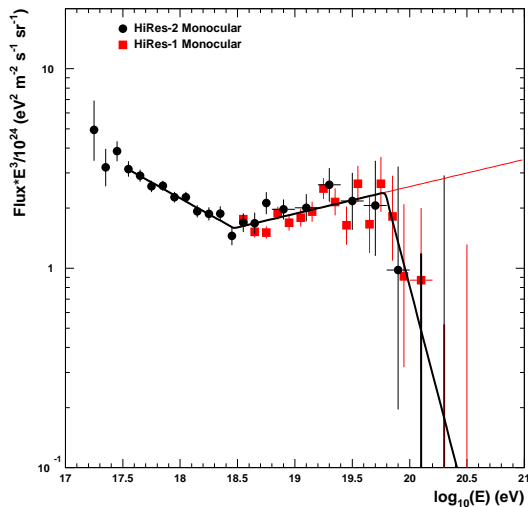


**Figure 2.** The HiRes monocular spectra fit to a simple power law with no break points. The parameters of the fit are given in Table ??.



**Figure 3.** The HiRes monocular spectra fit to a broken power law with one floating break point. The parameters of the fit are given in Table ??.

The simple power law fit is clearly not a good fit. Adding a floating break point gives a much better fit, and the break point finds the feature known as the Ankle with a very high degree of statistical significance. Adding a second floating break point improves the fit further, reducing the  $\chi^2$  by nearly 16 while adding only 2 parameters. The break



**Figure 4.** The HiRes monocular spectra fit to a broken power law with two floating break points. The parameters of the fit are given in Table ???. The red line shows an extension of the middle section of the fit above the second break point; this is used to calculate the significance of the second break point and to calculate the expected integral spectrum in the  $E_{1/2}$  calculation.

**Table 1.** Parameters found in broken power law fits to the HiRes monocular spectra.

Fit	$\chi^2/\text{DOF}$	$\gamma$	BP	$\gamma$	BP	$\gamma$
0 BP	114/37	$3.12 \pm 0.01$				
1 BP	46.0/35	$3.31 \pm 0.03$	$18.45 \pm 0.02$	$2.91 \pm 0.03$		
2 BP	30.1/33	$3.32 \pm 0.04$	$18.47 \pm 0.06$	$2.86 \pm 0.04$	$19.79 \pm 0.09$	$5 \pm 1$

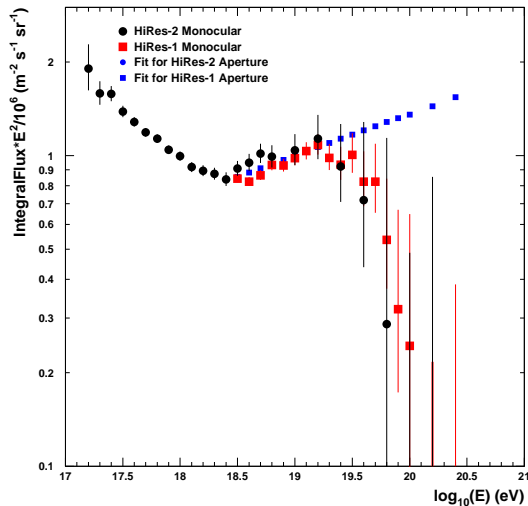
point is found to be at approximately the energy expected of the GZK suppression[?]. This will be discussed further below.

The statistical significance of the second break in the spectrum can be estimated by looking at the reduction in the  $\chi^2$  achieved by adding the break point, or by comparing the number of expected events above the second break point to what would be expected if the spectrum continued unabated above the second break point. The reduction of 16 in the  $\chi^2$  for two additional degrees of freedom corresponds to just under  $4\sigma$  significance in a gaussian fit. Using the red line in Figure ??, one would expect to see 28.0 events, where 11 events were actually observed. The Poisson probability of observing 11 events or fewer when expecting 28.0 is  $2.4 \times 10^{-4}$ . For comparison, the area in one tail of a gaussian distribution outside of  $4\sigma$  ( $3\sigma$ ) is  $3.2 \times 10^{-5}$  ( $1.4 \times 10^{-3}$ ). So the significance of the high energy suppression is between  $3\sigma$  and  $4\sigma$ .

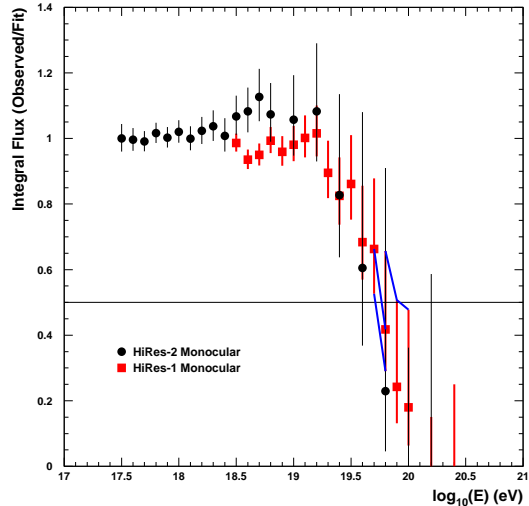
## 2. The Integral Spectrum and $E_{1/2}$

Berezinsky *et al.*[?] have suggested measuring the energy of a break in the UHECR spectrum finding the energy,  $E_{1/2}$ , at which the observed integral spectrum is half of what one would expect with no break. The integral spectrum measured by HiRes,

along with the expected integral spectrum using the red line in Figure ??, is shown in Figure ?. The ratio of the observed to the expected integral spectra is shown in Figure ?.



**Figure 5.** The integral spectra derived from the differential spectra shown in Figure ?. The blue points represent the expected integral spectrum from the red line in that figure.



**Figure 6.** The ratio of the observed to the expected integral spectra. Since the uncertainties between adjacent bins are correlated, the value of  $E_{1/2}$  and its uncertainty are obtained by a simple interpolation between the central values and uncertainties of the HiRes-I points as indicated by the blue lines.

By interpolating between the HiRes-I points in Figure ?, we find an experimental value of  $\log_{10} E_{1/2} = 19.77^{+0.15}_{-0.06}$  ( $E$  in eV). Berezhinsky *et al.*[?] have determined  $\log_{10} E_{1/2} = 19.72$  as what is to be expected for the GZK suppression for  $2.1 < \gamma < 2.7$ .

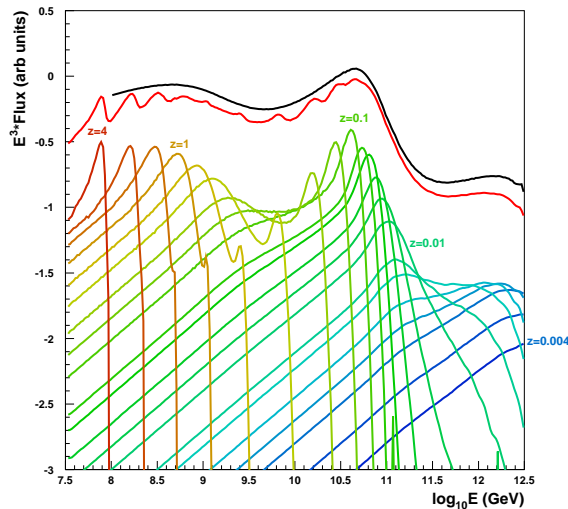
### 3. Uniform Source Model Fits

Berezhinsky *et al.*[?] also calculate the energy loss rate for UHE protons traveling through the cosmic microwave background radiation (CMBR) assuming continuous energy loss through electron pair production, pion production and universal expansion. Using these energy loss rates together with a model of the distribution of extragalactic UHECR sources allows one to predict the observed spectrum of extragalactic protons for a given input spectrum.

Since protons with energies above the pion production threshold lose energy in highly inelastic interactions, we have used the Monte Carlo method of DeMarco *et al.*[?] to model this part of the propagation of extragalactic protons. Protons from a shell

at a given redshift are propagated from generation to observation (at  $z = 0$ ). A given input energy results in a distribution of observed energies after such a propagation. This  $E_{\text{in}}-E_{\text{out}}$  function convolved with the input spectrum gives the observed spectrum for protons from sources at a given redshift.

If the distribution of sources is assumed to be uniform at any given redshift, but to evolve with redshift as  $(1+z)^m$ , one can combine the spectra from different shells, weighting each shell accordingly. This is demonstrated with a coarse, logarithmic series of shells in Figure ??.

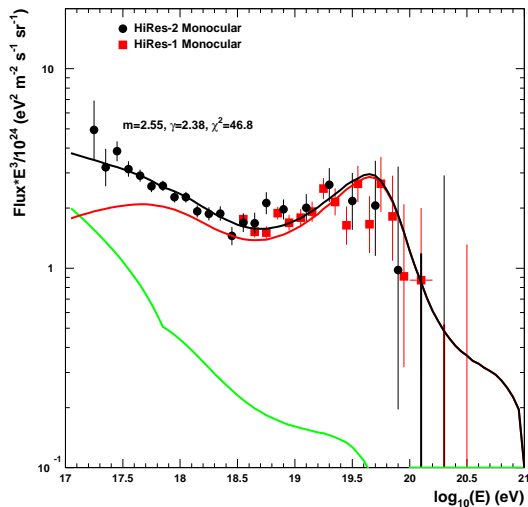


**Figure 7.** Predicted spectrum of extragalactic protons from the uniform source model with an input spectral slope  $\gamma = 2.4$  and an evolution parameter  $m = 2.5$ . The series of spectra colored blue to red at the bottom show the spectra from sources in given shells, weighted appropriately. The red line shows the sum of the shown shells. The black line shows the sum of a much finer set of shells.

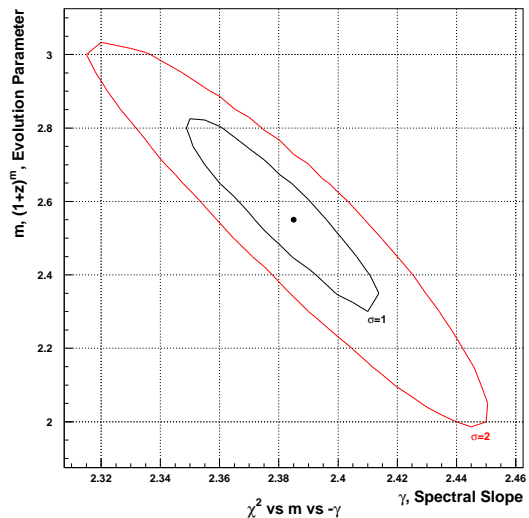
Because the HiRes-II spectrum extends to fairly low energies, one should take into account an additional galactic component when fitting to this USM model. We made the simple phenomenological assumption that the extragalactic and galactic components of the spectrum are expressed, respectively, in the light (protons) and heavy (iron) components of a composition measurement. We use fits to the HiRes Prototype/MIA[?] and HiRes Stereo[?] composition measurements with respect to QGSJet proton and iron expectations to determine the relative sizes of the extragalactic and galactic components. Then, for a given set of parameters for the extragalactic UHECR spectrum, we can add the appropriate galactic cosmic ray flux.

We varied the input spectral slope,  $\gamma$ , and evolution parameter,  $m$ , to find the best fit of the HiRes monocular data to this USM-plus-Galactic model. The best fit spectrum is shown in Figure ??, while the statistical uncertainties in the  $m$ - $\gamma$  plane are shown in Figure ??. By varying the heavy/light fit within the uncertainties of the composition measurements, and refitting the USM-plus-Galactic model with this new extragalactic/galactic ratio allows one to estimate the systematic uncertainty in the fit. The final result for the extragalactic USM model is  $\gamma = 2.38 \pm 0.035(\text{stat}) \pm 0.03(\text{syst})$ ,  $m = 2.55 \pm 0.25(\text{stat}) \pm 0.30(\text{syst})$ .

The fit works best in the region on either side of the Ankle, with the fall at lower energies, into the ankle, primarily determining  $m$ , and the rise at higher energies, out



**Figure 8.** Best fit of the USM-plus-Galactic model to the HiRes monocular spectra. The red line shown the extragalactic component, the green line shows the galactic component and the black line shows the sum.



**Figure 9.** The  $1\sigma$  and  $2\sigma$  uncertainty contours for the fit shown in Figure ??.

of the Ankle, primarily determining  $\gamma$ . The fit does not work as well in the region just below the GZK suppression. This could be due to some sources having a maximum energy below the GZK threshold. There is also little sign of a Second Knee at around  $10^{17.5}$  eV, though the HiRes-II data has little statistical power in this region.

#### 4. Conclusion

The HiRes detector has observed the Ankle and has evidence for a suppression at higher energies above  $10^{19.8}$  eV. The energy for this high energy suppression agrees with what is expected from the GZK suppression according to the  $E_{1/2}$  test. The observed spectra are well fit by a USM-plus-Galactic model, which finds an input spectral slope for extragalactic protons of  $\gamma = 2.38 \pm 0.035(\text{stat}) \pm 0.03(\text{syst})$ , and an evolution parameter  $m = 2.55 \pm 0.25(\text{stat}) \pm 0.30(\text{syst})$ .

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