International Journal of Modern Physics A

Fitting the HiRes Spectra and Monocular Composition

Douglas R Bergman, presented on behalf of the High Resolution Fly's Eye Collaboration
Rutgers, The State University of New Jersey
Department of Physics and Astronomy
Piscataway, New Jersey, USA 08854

Received (Day Month Year)
Revised (Day Month Year)

In the first section, we discuss our fits to the latest HiRes monocular spectra. We find that the best fit for the extragalactic component has a spectral index of $\gamma = -2.38 \pm 0.04$ with a distribution of sources varying with a evolution parameter $m = 2.8 \pm 0.3$. In the second section, we discuss preliminary results from a new composition measurement using HiRes monocular data. We find a predominantly light spectrum above $10^{17.6}$ eV.

1. Fitting the HiRes Spectra

In fitting the spectrum of ultra high energy cosmic rays (UHECRs), we use use a toy model in which composition determines source. In this model, we use the recent composition measurements of the HiRes Prototype/MIA experiment[1] and of HiRes in stereo mode[2]. The light component is identified with the extragalactic UHECRs; the heavy component with galactic UHECRs.

We fit the extra galactic component assuming the protons have lost energy between acceleration and observation, and that the sources are distributed uniformly, with a density that is smoothly varying in time. The fits assume a power law spectrum, $E^{-\gamma}$, with a spectral index γ identical for all sources. We use the average energy loss model of Berezinsky *et al.*[5] to find the observed spectrum from a source a given redshift. In addition, we use a Monte Carlo (MC) simulation[6] for the discrete energy losses associated with pion production. The MC is only important for propagating particles from small redshifts, $z < 0.1$.

The fits are performed by varying the normalization, the spectral slope (γ), and the evolution parameter (m). The goodness-of-fit is evaluated using the binned-maximum-likelihood method.

The result of the fit to the most recent HiRes-I[7] and HiRes-II[8] monocular spectra is $\gamma = -2.38 \pm 0.04$ and $m = 2.8 \pm 0.3$. This fit is shown on the left in Figure 1. The quoted uncertainties include the effect of the correlation between γ and m. This correlation is shown on the right in Figure 1. Not included in this fit are any systematic uncertainties. The largest systematic uncertainty is expected to be due to the details of composition used in the aperture calculation for the HiRes-II spectrum. Changes in the composition tend to move the best fit point along the trough of Figure 1, changing the m vs. γ relationship little.

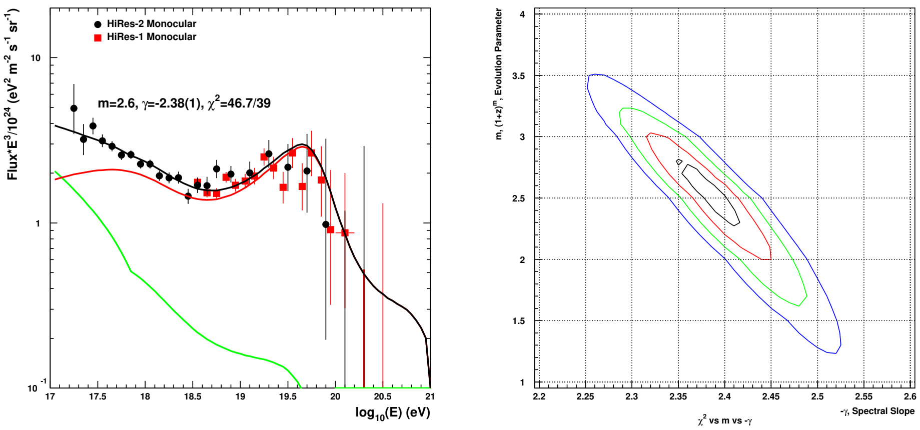

Fig. 1. Left Side: The HiRes-I and HiRes-II monocular spectra, with the result of the best fit spectrum. HiRes-I points are shown as red squares, HiRes-II points as black circles. The one σ upper limit on the flux in two more bins for each measurement are shown above the highest energy actually observed. The black fit line is the sum of the galactic (green) and extragalactic (red) components. The parameters of the extragalactic component are $\gamma = -2.38$ and $m = 2.6$. There are 42 data points, giving 39 degrees of freedom in the fit. Right Side: A scan of χ^2 ($-2 \log L$) in m-γ space. The first four σ contours are shown.

2. HiRes Monocular Composition Measurement

Because the uncertainty in composition is a large part of the uncertainty in the parameters in the fit to the spectrum, we were motivated to improve the composition measurement, especially below 10^{18} eV. This requires using the HiRes-II monocular data set.

The limited elevation coverage of the HiRes-II aperture biases our $X_{\max}$ acceptance, with the bias increasing at lower energies. The bias comes from requiring that $X_{\max}$ be observed by the detector. Events close to the detector are more likely to have $X_{\max}$ above the visible range. Lower energy events are observed closer to the detector, and will have a larger bias than those at high energies. This bias precludes performing an elongation rate analysis at energies below 10^{18} eV.

Instead, we fit the $X_{\max}$ distribution, in energy bins, to a combination of MC $X_{\max}$ distributions from protons and from iron. The fit is performed using the binned maximum likelihood technique as implemented in the HBOOK[9] routine HMCLNL. The uncertainty of the fit in each energy bin is taken from the width of $-2 \log L$ as fit to a quadratic in the region about the maximum. The result of these fits for the data at all energies is shown on the right of Figure 2.

This fit gives only the proportion of proton and iron in the accepted sample and must be corrected to find the true composition. However, the raw composition can be tested on a MC sample where one knows the type of each event. The result of this MC analysis is shown on the left in Figure 2. The fits agree very well with what is actually in the sample.

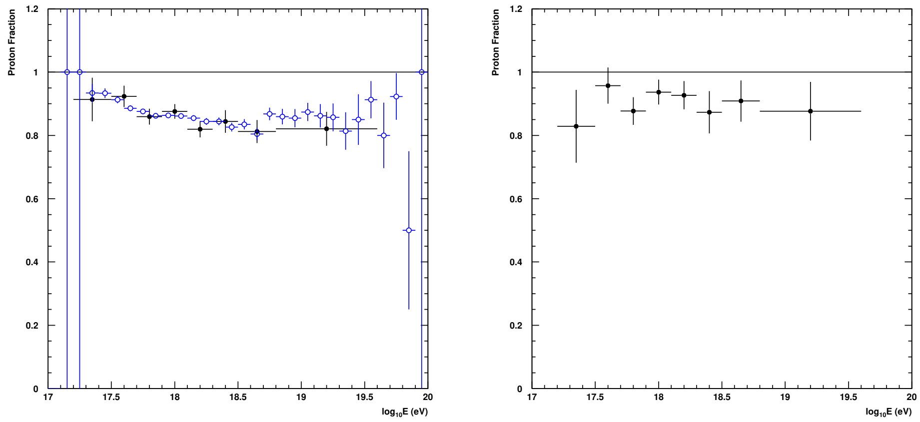

Fig. 2. Left Side: The raw composition measured in the MC sample used in the spectrum calculation. The black, filled circles are the result of the fits. The blue, open circles are the actual fractions using the known, *a priori* information available in the MC sample. Right Side: The raw composition measured in the data.

The raw composition measurements are corrected using the relative acceptances in the proton and iron MC samples.

The corrected composition for the MC sample is shown on the left in Figure 3. We can compare the results to the known input: the HiRes Prototype/MIA and HiRes Stereo composition measurements. The corrected results of the fits agree very well with the inputs to the MC.

Finally, we show as a very preliminary result, the corrected proton-iron ratio for the data. See the right side of Figure 3. This result shows a very light composition (90% protons) above $10^{17.6}$ eV. Below this energy we measure a sharply lower composition, but with large uncertainties because of few events and a large acceptance correction. The measured composition at high energies is in agreement with the HiRes Stereo measurement, but closer to being all protons.

The data used in the fits comes from the same data set used in the HiRes-II spectrum analysis which was fit above. A considerable amount of data, about a factor of three more, was collected after this data set. This later data was collected with lower light thresholds, and as such, will have a lower energy threshold. In addition, the aperture at each energy will be increased, reducing the size of $X_{\max}$ biases. Performing this analysis on this expanded data set should give us much

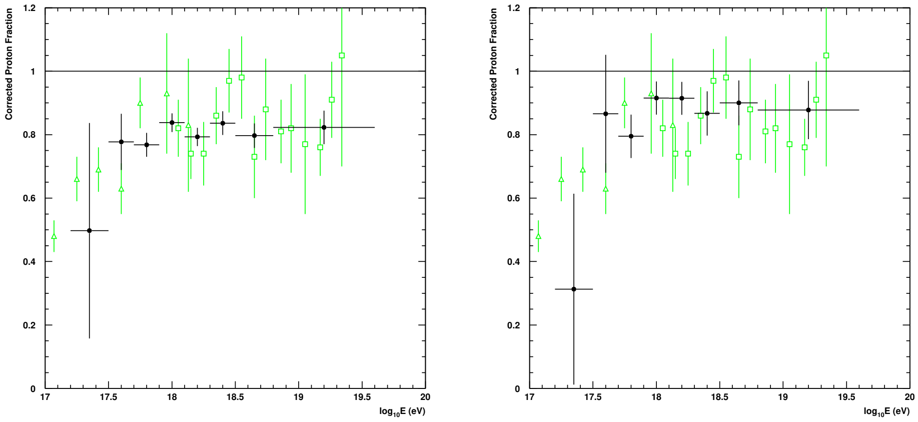

Fig. 3. Left Side: The corrected composition measured in the MC sample used in the spectrum calculation. The black, filled circles are the corrected result of the fits. The green, open triangles and squares are the HiRes Prototype/MIA and HiRes Stereo composition measurements which form the input to the MC. Right Side: The preliminary, corrected composition measured in the data. The black, filled circles are the corrected result of the fits. For comparison, the HiRes Prototype/MIA and HiRes Stereo composition measurements are shown as green, open triangles and squares, respectively.

tighter constraints on the composition in the middle of the 10^{17} eV energy decade.

The Telescope Array (TA), which has already received Japanese funding, and the TA Low Energy extension (TALE) will be able to push this analysis even further. TALE will use the HiRes phototubes with larger mirrors to push the thresholds even lower. The mirrors will be arranged in a tower rather than a ring to avoid biases in $X_{\max}$. Geometrical resolution at the level of HiRes Stereo will be provided by coincidences with the TA ground array.

References

1. T. Abu-Zayyad, *et al.*, Phys. Rev. Lett. **84** (2000) 4276.
2. G. Archbold and P.V. Sokolsky (for the HiRes Collaboration), Proc. of the 28th Int. Cosmic Ray Conf. (2003) 405.
3. D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz and T. Thouw "CORSIKA : A Monte Carlo Code to Simulate Extensive Air Showers", Report FZKA 6019 (1998), Forschungszentrum Karlsruhe.
4. N.N. Kalmykov, S.S. Ostapchenko and A.I. Pavlov, Nucl. Phys. B (Proc. Suppl.) **52B**, 17, (1997).
5. V. Berezinsky, A.Z. Gazizov, S.I Grigorieva, hep-ph/0204357.
6. De Marco, Blasi, Olinto, Astropart. Phys. **20** (2003) 53.
7. R.U. Abassi *et al.*, Phys. Rev. Lett. **92**, (2004) 151101.
8. A. Zech, proceedings of CRIS 2004.
9. HBOOK Manual. `http://wwwasdoc.web.cern.ch/wwwasdoc/hbook_html3/hboomain.html`