Fits of the HiRes Spectrum to Astrophysical Models

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Abstract

HiRes has recently published monocular measurements of the UHECR spectrum. These spectra are not consistent with a continuation of the spectrum above $10^{19.8}$ eV at the same spectral slope as observed below that energy. We fit the published spectra to a two component source model with galactic and diffuse extra-galactic sources. The extra-galactic component of the spectrum is modified for the passage of the UHECRs through the intra-galactic medium using the analytic formalism of Berezinsky *et al.* These models fit the spectra well because they produce the recognized features of the second knee, the ankle, and the GZK cutoff.

1. Introduction

AGASA[10, 12] has published evidence for a continuation of the UHECR spectrum above the energy of the GZK cutoff[8, 13]. This has led to a great deal of theoretical speculation on the sources and propagation of UHECRs in an effort to produce a model without the cutoff. HiRes has recently published its first measurements of the UHECR spectrum, using each of its two sites in monocular mode[2, 3]. These spectra are consistent with a cutoff at the expected energy. We will evaluate the statistical significance of this break in the spectrum and fit the spectra to determine how well they conform to what is expected from UHECR sources distributed diffusely in the universe.

2. Continuation Above the GZK Energy

To evaluate the significance of the reduction in the flux above $10^{19.8}$ eV in the HiRes spectra, we fit the spectra between the ankle and the GZK energy to

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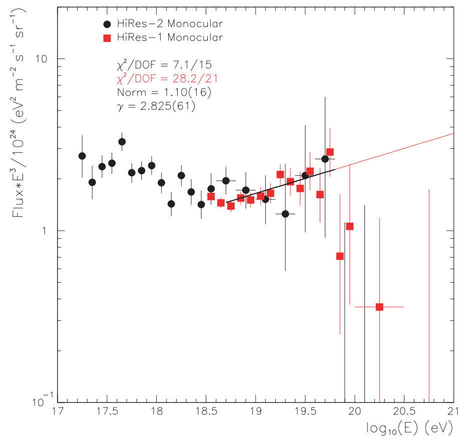

Fig. 1. An $NE^{-\gamma}$ fit to HiRes spectra above the ankle.

$NE^{-\gamma}$. In this fit, and the fits below, we compared the numbers of events observed in energy bins to the numbers of events expected, using the binned maximum likelihood method. This allows us to deal with bins containing few or no events. The error bars on the E^3J plots are determined from the likelihood of having observed the given number of events using Poisson statistics. The calculation of the expected numbers of events from the flux requires knowledge of the aperture, which is a monotonically increasing function of the energy. We use the nominal apertures from reference [3].

The fit from $10^{18.7}$ to $10^{19.8}$ eV, gives $\chi^2 = 7.1$ for 15 DOF, with $\gamma = 2.825 \pm 0.061$. If we now fix the parameters at these fitted values and extend the range over which the χ^2 is calculated to the highest energies, we find that χ^2 increases by 21.1 for 6 additional DOF. The fit and its extension are shown in Fig. 1. The numbers of observed and expected events are given in Table 2. For energies above $10^{19.8}$ eV, HiRes observes 5 events where one would expect 21.7. The probability of observing 5 or less events when expecting 21.7 is 1.8×10^{-5}.

3. Energy Losses by UHECR

Since there is a change in the spectral index of the HiRes spectra above $10^{19.8}$ eV, we turn to astrophysical sources and energy loss mechanisms to explain the details of the spectrum. Above the GZK energy, protons interact with CMB photons to create pions, causing the proton to lose energy. Equally important for fitting the spectrum, is the lower energy threshold for the proton to lose energy in producing e^+e^- pairs. The energy threshold for electron pair production is $10^{17.6}$ eV, becoming fully effective at $10^{18.5}$ eV.

To account for both these energy loss processes, we use the continuous

Table 1. Expected and observed numbers of events in a fit to $NE^{-\gamma}$ with $\gamma = 2.825$.

	$\log E$ (eV)	Observed	Expected
HiRes-I	19.8-19.9	2	6.5
	19.9-20.0	2	4.6
	20.0-20.5	1	7.6
	20.5-21.0	0	1.0
HiRes-II	19.8-20.0	0	1.1
	20.0-20.2	0	0.9

energy loss formalism of Berezinsky *et al*[4, 5]. The energy history for a given observed energy is computed as a function of red-shift z. For a given input spectrum at a given epoch, one calculates the observed spectrum at the current epoch. For a given distribution of sources at different epochs, one adds up the effects from shells of sources at each epoch.

4. Source Models

All of our fits assume two components for the UHECR spectrum. One component, consisting of protons, has sources distributed diffusely throughout the universe, and a power-law spectrum at the source modified by the energy loss mechanisms described above. The other component, consisting of iron nuclei, has sources within our own galaxy and is described phenomenologically by an E^{-3} spectrum, cut off by a linear factor in $\log E$, going from 1 at 10^{17} eV to 0 at $10^{19.5}$ eV. The two component model is motivated by the measured change in composition, from heavy to light, as measured by Fly's Eye[6] and the HiRes/MIA[1].

The left side of Fig. 2. shows the result of a fit of the HiRes spectra to a source model with a uniform density of sources that does not evolve as a function of the red-shift. The figure explicitly displays the expected contribution of each component along with the the resulting fit. The fit is notable for its agreement with the data in three features. It matches the reduction in flux at the highest energies, which in this model is the GZK cutoff. As important, however, because of the much greater number of events included, is the agreement in the second knee and ankle. These features are attributable to electron pair production energy losses.

We varied the source spectrum by allowing the extragalactic source density to evolve with the red-shift z as $(1+z)^m$. We also modified the source distribution by taking into account the relative density of luminous matter as measured by galactic surveys[7, 11]. Our best fit comes with using the galactic survey information and an m of 3. This fit is shown on the right side of Fig 2. The rate of star formation also goes as $(1+z)^3$[9].

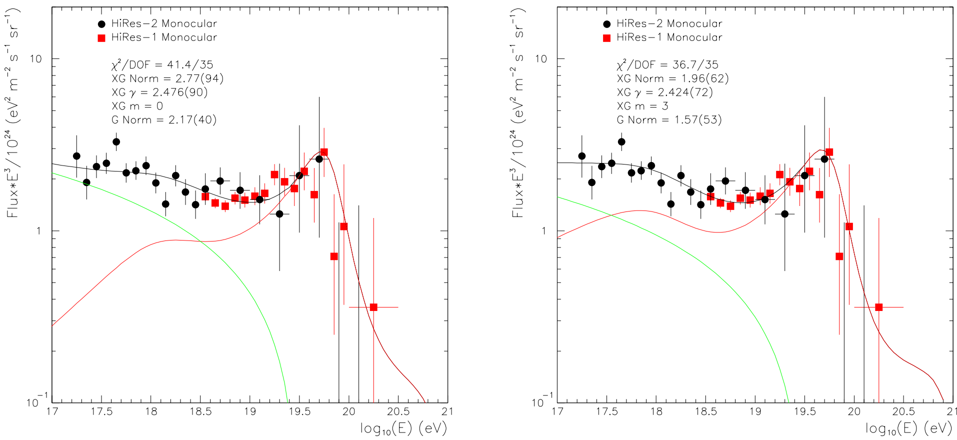

Fig. 2. Fits to the HiRes spectra of the two component source model discussed in the text. The left panel shows a fit with uniformly distributed extragalactic sources that do not evolve as a function of z. The right panel shows a fit with a source distribution modified by the relative density of luminous matter as measured in galaxy surveys and evolving as $(1+z)^m$ with $m = 3$.

5. Conclusion

We find the HiRes spectra are not consistent with an unbroken continuation above the GZK energy. Instead, we find that fits using a two component model motivated by composition measurements and using well-understood energy loss mechanisms can explain all the features apparent in the HiRes spectra.

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