A BREAK IN THE HIGHEST ENERGY COSMIC RAY SPECTRUM: A SIGNATURE OF NEW PHYSICS?

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ABSTRACT

Recent experimental data from the Fly's Eye and the Akeno array seem to indicate significant structure in the ultrahigh energy cosmic ray spectrum above 10^{18} eV. A statistically significant dip has been established at about 5×10^{18} eV. In addition, each experiment observed a different superhigh energy event above 10^{20} eV separated from the rest of the data by about half a decade in energy. In this article we discuss what this implies for the existence or non-existence of the "Greisen-Zatsepin-Kuz'min cutoff", a long lasting and still open question in cosmic ray physics. This cutoff, caused by energy losses in the cosmic microwave background, is predicted to occur at a few times 10^{19} eV if cosmic rays are produced by shock acceleration of lower energy particles at extragalactic distances. We show that from the spectral point of view, sources nearer than a few Mpc are still consistent with the data at the 1σ level, provided these sources accelerate particles beyond 3×10^{20} eV. However, persistence of the apparent gap in the existing data at the level of a 4 times higher total exposure would rule out a wide range of acceleration models at 98% C.L., whether they rely on nearby or extragalactic sources. This might hint to the existence of a "top down" mechanism which produces an additional hard component of ultrahigh energy particles directly, say, by decay from some higher energy scale in contrast to bottom up acceleration of charged particles. In this scenario a cutoff followed by a pronounced spectral flattening and possibly even a gap could naturally be formed.

1 Introduction

For almost thirty years it has been clear that the cosmic microwave background (CMB) has profound implications for the astrophysics of ultrahigh energy cosmic rays (UHE CR). Most notably, nucleons are subject to photopion losses on the CMB which lead to a steep drop in the interaction length at the threshold for this process at about 6×10^{19} eV. This effect is known as the Greisen-Zatsepin-Kuz'min (GZK) effect [1, 2]. For heavy nuclei the giant dipole resonance which leads to photodisintegration produces a similar effect at about 10^{19} eV [3]. One of the major unresolved questions in cosmic ray physics is the existence or non-existence of a cutoff in the UHE CR spectrum below 10^{20} eV which could be attributed to these effects if the sources are further away than a few Mpc.

The interest in this question has renewed since recently events with energies above the GZK cutoff have been detected [6, 7, 8, 9, 10, 11, 12]. Most strikingly, both the Fly's Eye experiment [9, 10] and the Akeno array [11, 12] detected a different superhigh energy event significantly beyond 10^{20} eV as well as an apparent gap of about half a decade in energy between the highest and second highest events. This led to a vigorous discussion on the nature and origin of these particles [13, 14, 15, 16]. In this article we show that the structure of the high energy end of the UHE CR spectrum has the potential to provide powerful constraints on a wide class of models for these extraordinary particles in the near future. The options discussed in the literature can be divided into two categories.

In "bottom-up" scenarios charged baryonic particles are accelerated to the relevant ultrahigh energies. This could, for example, be achieved by ordinary first order Fermi acceleration at astrophysical shocks [17] or by linear acceleration in electric fields as they could arise for instance in magnetic reconnection events [18]. The resulting injection spectrum of the charged primaries at the source is typically a power law in energy E, $j_{\rm inj}(E) \propto E^{-q}$. In the case of reconnection acceleration there is no clear-cut prediction for the power law index q, but in case of shock acceleration it satisfies $q \geq 2$. We will refer to this latter case in what we call conventional bottom-up acceleration scenarios in the following. Secondary neutral particles like γ-rays and neutrinos are only produced by primary interactions in these scenarios [19].

In top-down scenarios the primary particles which can be charged or neutral are produced at ultrahigh energies in the first place, typically by quantum mechanical decay of supermassive elementary "X" particles related to Grand Unified Theories (GUT's). Sources of such particles today could be topological defects (TD's) left over from early universe phase transitions caused by spontaneous breaking of symmetries underlying these GUT's [20]. Generic features of these scenarios are injection spectra considerably harder (i.e. flatter) than in case of bottom-up acceleration and a dominance of γ-rays in the X particle decay products[21]. Even monoenergetic particle injection beyond the GZK cutoff can lead to rather hard spectra above the GZK cutoff [22].

The distinction between these scenarios is closely related to the existence or non-existence of the GZK cutoff in the form of a break in the spectrum. In contrast to the bottom-up scenario alone, the hard top-down spectrum is able to produce a pronounced recovery in the form of a flattening beyond the "cutoff" which could explain the highest energy events and possibly even a gap.

2 Likelihood Analysis

For the statistical analysis we assume that the data are represented as the number of observed events, n_i, within a given energy bin i, where $i = 1, \cdots, N$. A given model predicts a certain observed differential flux $j(E)$ (in units of particles per unit area, unit time, unit solid angle and unit energy). For this model the number of expected events, μ_i, in energy bin i is then given by

$$\mu_i = \int_{E_i^{\min}}^{E_i^{\max}} dE\, j(E) A(E)\,, \tag{1}$$

where $A(E)$ is the total exposure of the experiment at energy E (in units of area times solid angle times time) and bin i spans the energy interval $\left[E_i^{\min}, E_i^{\max}\right]$. Both the Fly's Eye and the Akeno experiment used equidistant bins in logarithmic energy space with $\log_{10}(E_i^{\max}/E_i^{\min}) = 0.1$. The likelihood function adequate for the low statistics problem at hand is then given by Poisson statistics as

$$L = \prod_{i=1}^{N} \frac{\mu_i^{n_i}}{n_i!} \exp[-\mu_i]\,. \tag{2}$$

Any free parameters of the theory are determined by maximizing the likelihood Eq. (2). In analogy to Ref. [11] we then determine the likelihood significance for the given theory represented by the set of (optimal) μ_i's. It is defined as the probability that this set of expectation values would by chance produce data with a likelihood smaller than the likelihood for the real data. This probability is calculated by Monte Carlo simulation.

We will perform the fits in the energy range between $10^{19}\,$eV and the highest energy observed in the respective experiment. For comparison we compute the significance of these fits in the range below the gap and in the range including the gap and the highest energy events separately. This will demonstrate the influence of this structure on the fit quality.

In determining the likelihood significance we also take the finite experimental energy resolution into account. For the statistical error we do that by folding the theoretical fluxes with a Gaussian window function in logarithmic energy space corresponding to an energy resolution of about 30%. We determine the effect of the systematic errors by repeating the procedure with data shifted systematically by $\pm 40\%$ in energy (see Tables 2 and 3).

Finally, for each model considered we simulate data for an exposure increased by a factor f assuming for this exposure level the persistence of the apparent gap and the flux associated with the highest energy events in the existing data. This is done in the following way: For a given model we determine the maximum likelihood fit to the real data as described above which results in a set of expectation values μ_i ($i = 1, \cdots, N$). For all bins up to the second highest energy observed we then draw random event numbers n_i' from Poisson distributions whose mean values are given by $\mu_i' = (f-1)\mu_i$. This assumes that the underlying model represents the data well below the gap (see Tables 2) and continues to do so for increased exposure. All other bins are assumed to contain no additional events, $n'_i = 0$, except for the highest energy bin for which we assume at least one more event, $n'_i \geq 1$. The simulated data set then consists of the sums of these numbers n'_i and the numbers n_i of events already counted. For this data set we compute the likelihood significance of the underlying model as above. By doing this many times one can determine for the given exposure enhancement the confidence level to which the given theory could be ruled out (or supported) if the gap structure should persist.

3 Input Models

Before we present the results, let us describe the models we use for $j(E)$. The Fly's Eye stereo data [9, 10] show a significant dip in the spectrum at around 5×10^{18} eV. In Ref. [9] this was attributed to the superposition of a steeper galactic component dominated by heavy nuclei and a flatter extragalactic component of light particles like nucleons or possibly also γ-rays. Above $\approx 10^{19}$ eV the latter one would thus dominate and a description by a power law is consistent with the existing data at least up to the GZK cutoff. For model 1 we therefore chose a power law with normalization and power law index q as free parameters. A power law continuing beyond the GZK cutoff could be produced in the following situations: First, there could be a nearby source (i.e. nearer than a few Mpc) of baryonic charged particles for which the (power law) injection spectrum is not noticeably modified and the GZK cutoff is irrelevant. Second, the observed flux could be dominated by neutral particles like γ-rays or even neutrinos [16] from a distant source [23]. Since in contrast to nucleons there are no resonance effects in the interactions of these particles around 10^{20} eV, their processed spectrum would have a smooth shape which could be approximated by a power law. The fits typically result in $q \approx 2.7$ and thus model 1 would belong to the bottom-up scenarios.

We also numerically calculated [24] the shape of the UHE CR spectrum from single sources at various distances and from uniformly distributed sources as it would be observed after propagation through the intergalactic medium. For all these cases we used power law injection of primary protons with cutoff energies $E_c \gg 10^{21}$ eV, and normalizations determined by maximizing the likelihood. Our code accounts for the propagation of the nucleon component and secondary γ-ray production as well as for γ-ray propagation. Since current experiments cannot distinguish between nucleons and a possible γ-ray component, we used the sum of their fluxes for $j(E)$. The secondary γ-ray flux depends somewhat on the radio background and the extragalactic magnetic field B [24]. In order to maximize the possible amount of recovery we assumed a comparatively weak radio background with a lower cutoff at 2MHz [25] and $B \ll 10^{-10}$G. For injection indices $q \geq 2$ the resulting fluxes are representative of acceleration models of UHE CR origin. For the diffuse spectrum from a uniform source distribution we assumed absence of source evolution and chose $q = 2.3$ which fits the data quite well below the gap (see Table 2). The maximal source distance $d_{\rm max} = 10^3$ Mpc was chosen in a range where $d_{\rm max}$ has no significant influence on the shape of the resulting spectrum above 10^{19} eV. The minimal source distance $d_{\rm min}$ was roughly chosen by maximizing the fit quality.

It turns out that a discrete source beyond a few Mpc alone cannot explain the data including the highest energy events. More interesting cases are a diffuse spectrum alone (model 2), and its combination with an additional discrete source at 10 Mpc (model 3), where in both cases $d_{\rm min} = 0$. In model 4 we combined a diffuse spectrum for $d_{\rm min} = 30$ Mpc with a nearby source, represented by an unprocessed power law with index $q = 2$. This model could be relevant if there were a strong galactic source which accelerates iron nuclei much beyond 10^{20} eV with the hardest injection spectrum possible for shock acceleration models ($q = 2$).

Since in top-down models the flux above the GZK cutoff could be dominated by γ-rays [21] the processed spectrum is somewhat uncertain due to interactions with unknown backgrounds [24]. However, the hard top-down component must be negligible below the GZK cutoff whereas above the cutoff it can be approximated by a power law. Similarly to model 4 we therefore chose best fit combinations of the diffuse bottom-up spectrum for $d_{\rm min} = 30$ Mpc with an unprocessed power law of index $q = 0.6$ as our model 5. Due to γ-ray propagation effects [24] the injection spectrum corresponding to this latter hard component could be considerably softer and consistent with various constraints on energy injection as long as the X particle mass is not too high [26, 27]. Model 5 acts as a generic example of how an additional hard top-down component might naturally produce a pronounced recovery, i.e. a spectral flattening. In fact we find that for $q < 1$ the number of events expected per logarithmic energy bin even starts to grow with energy beyond a few times 10^{20} eV although the actual differential flux is always a decreasing function of energy. Indeed, this can naturally give rise to a gap in the measured spectrum.

In Table 1 we summarize the main characteristics of the representative models 1-5 discussed above.

4 Results

Table 2 presents the results for the Fly's Eye and Akeno data available today for the models discussed in the previous section. Below the gap a diffuse spectrum (model 2) is favored by the data. Additional discrete sources beyond a few Mpc (model 3) do not improve the fit significantly. There is thus no indication of a significant "bump" below the GZK cutoff which would be produced by strong discrete sources [28]. If one includes the gap and the highest energy events into consideration, an exclusive diffuse bottom up component is ruled out at 90% C.L. In contrast, bottom-up sources nearer than a few Mpc are consistent with the data at the 1σ level. Nevertheless, since there are no obvious visible source candidates near the arrival directions of the highest energy events observed, this is a highly problematic option, as was argued in Ref. [15]. Fig. 1A shows the result of fitting the power law model 1 to the Fly's Eye data from 10^{19} eV up to the highest energy event. The best fits in this energy range, however, are produced by combinations of a diffuse component with a hard unprocessed power law (models 4 and 5). Fig. 2A shows the result for the exotic model 5.

Table 3 summarizes the results obtained from the simulated "data" for a quadrupled exposure assuming that the gap and the comparatively high flux in the highest energy bin persists at this exposure. The constraints on the models get much more stringent. Indeed, all curves predicted from bottom-up models (model 1 to 4) can be ruled out at least at the 98% C.L., except the most optimistic bottom-up model 4 involving a strong nearby (supposedly iron) source, which could be ruled out only at about 90% C.L. The basic reason is the following: Local sources can reproduce the superhigh energy events, but at the same time predict events in the gap which are not seen. Sources beyond about 20 Mpc on the other hand predict a GZK cutoff and a recovery which is much too weak to explain the highest energy events. This conclusion can only be evaded by assuming a systematic shift in observed energies of the order of 40% or larger. Fig. 1B shows a typical example for fitting model 1 to data simulated for a quadrupled Fly's Eye exposure.

In contrast, the representative model with a top-down component is typically consistent at the 1σ level as long as the shape of the gap is not too discontinuous. Fig. 2B shows a typical situation where the exotic model 5 is fitted to simulated data. Thus, if the observed gap structure should persist within a quadrupling of the data set it would be a statistically significant proof of the need for new exotic physics. We should stress that the significance for this would get even more stringent if high fluxes would continue considerably beyond the highest energies detected to date. Conversely, if the gap structure should disappear and the flux in the highest energy bins is not too high, there would be no immediate need for new physics except for the non-trivial problem of acceleration to such high energies [29]. A decisive answer should definitely be possible with the proposed Giant Air Shower Array [30] since it would allow enhancing the exposure by much more than a factor 4. This instrument should also be able to measure the composition of the UHE CR flux.

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Figure Captions

Fig. 1. Maximum likelihood fits of the pure power law model 1 over the energy range $10^{18.95}\,\mathrm{eV} \leq E \leq 10^{20.55}\,\mathrm{eV}$. We fitted the effective flux (dashed lines) which results from the real differential flux (solid lines) by taking the experimental finite energy resolution into account. The data are given as 68% C.L. error bars or as 84% C.L. upper limits. Note that for illustration purposes we multiplied the steeply falling flux by E^3. (**A**) shows the fit to the actual Fly's Eye monocular data and corresponds to a likelihood significance of 46% in the gap region including the highest energy event. (**B**) presents a typical example resulting from "data" simulated for an exposure enhanced by a factor 4 as described in section 2. For these data model 1 would be ruled out at the 98% C.L.

Fig. 2. Same as Fig. 1 but for the exotic model 5. In contrast to the pure power law model 1 the likelihood significance in the gap region (87% and 47% in case of (**A**) and (**B**), respectively) typically stays within the 1σ level for both exposures.

Table 1. Summary of models used for the fits to the data. The models consist of uniformly distributed sources (diffuse component), a single source (discrete component) or a combination of these. We give the source distance or range of source distances d and the power law injection index q. For a discrete source at $d = 0$ the power law injection spectrum is unmodified. The normalizations of the components are fitted to the data.

	diffuse component	discrete component
model 1	–	$d = 0$, q fitted
model 2	$0 \leq d \leq 10^3\,\mathrm{Mpc}$, $q = 2.3$	–
model 3	$0 \leq d \leq 10^3\,\mathrm{Mpc}$, $q = 2.3$	$d = 10\,\mathrm{Mpc}$, $q = 2.3$
model 4	$30\,\mathrm{Mpc} \leq d \leq 10^3\,\mathrm{Mpc}$, $q = 2.3$	$d = 0$, $q = 2.0$
model 5	$30\,\mathrm{Mpc} \leq d \leq 10^3\,\mathrm{Mpc}$, $q = 2.3$	$d = 0$, $q = 0.6$

Table 2. Likelihood significances for fits of various models to the experimental data. The first number in each model row is for the Fly's Eye monocular data and the second number is for the Akeno data. The fits were performed between 10^{19} eV and the bin containing the highest energy observed, corresponding to $E_{\rm max} = 10^{20.55}$ eV and $E_{\rm max} = 10^{20.4}$ eV, respectively. Significances are given for the energy range below and above the second highest event separately (left and right part). We used the best experimental energy estimate ("central") as well as energies shifted systematically by $\pm 40\%$.

	$[10^{19}\,\mathrm{eV} - 10^{19.9}\,\mathrm{eV}]$			$[10^{19.9}\,\mathrm{eV} - E_{\rm max}]$		
	central	-40%	$+40\%$	central	-40%	$+40\%$
model 1	0.58	–	–	0.46	–	–
	0.59	–	–	0.39	–	–
model 2	0.78	0.39	0.85	0.12	0.12	0.094
	0.51	0.48	0.35	0.094	0.13	0.05
model 3	0.81	0.38	0.91	0.10	0.13	0.16
	0.52	0.49	0.47	0.19	0.25	0.20
model 4	0.75	0.34	0.88	0.49	0.35	0.67
	0.46	0.43	0.42	0.54	0.45	0.67
model 5	0.81	0.37	0.79	0.87	0.73	0.95
	0.57	0.48	0.45	0.87	0.74	0.94

Table 3. Same as for Table 2 but using "simulated data" for a quadrupling of experimental exposures assuming persistence of the gap structure (see section 2). The likelihood significances are here only given for the energy range of the gap including the highest energy observed. "1σ" indicates that the model typically agrees with the simulated data within the 1σ level as long as the gap is not too discontinuous. Note that the Akeno sample is in general less restrictive for the bottom-up scenarios since it corresponds to a smaller exposure than the Fly's Eye sample.

	$[10^{19.9}\,\mathrm{eV} - E_{\mathrm{max}}]$		
	central	-40%	$+40\%$
model 1	$\lesssim 0.02$	$-$	$-$
	$\lesssim 0.12$	$-$	$-$
model 2	$\lesssim 0.02$	$\lesssim 0.005$	$\lesssim 0.05$
	$\lesssim 0.02$	$\lesssim 0.02$	$\lesssim 0.04$
model 3	$\lesssim 0.02$	$\lesssim 0.003$	$\lesssim 0.05$
	$\lesssim 0.06$	$\lesssim 0.02$	$\lesssim 0.07$
model 4	$\lesssim 0.15$	$\lesssim 0.01$	$\lesssim 0.3$
	$\lesssim 0.12$	$\lesssim 0.03$	$\lesssim 0.25$
model 5	1σ	$\lesssim 0.05$	1σ
	1σ	$\lesssim 0.11$	1σ