ARTICLE IN PRESS
COMREN:3113

C. R. Physique ••• (••••) •••–•••

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Ultra-high-energy cosmic rays / Rayons cosmiques de ultra-haute énergie

# The flux suppression at the highest energies

## *La suppression du flux aux plus hautes énergies*

Diego Harari

*Centro Atómico Bariloche and Instituto Balseiro, San Carlos de Bariloche, Argentina*

A R T I C L E   I N F O

*Article history:*
Available online xxxx

*Keywords:*
Cosmic rays
Ultra-high energies
GZK

*Mots-clés :*
Rayons cosmiques
Ultra-hautes énergies
GZK

A B S T R A C T

Almost half a century ago, Greisen, Zatsepin and Kuz'min (GZK) predicted a "cosmologically meaningful termination" of the spectrum of cosmic rays at energies around $10^{20}$ eV due to their interaction with the cosmic microwave background, as they propagate from distant extragalactic sources. A suppression of the flux above $4 \times 10^{19}$ eV is now confirmed. We argue that current data are insufficient to conclude whether the observed feature is due to energy loss during propagation, or else to the fact that the astrophysical accelerators reach their limit, or indeed to a combination of both source properties and propagation effects. We discuss the dependence of the spectral steepening upon the cosmic-ray composition, source properties, and intervening magnetic fields, and speculate on the additional information that may be necessary to reach unambiguous conclusions about the origin of the flux suppression and of the mechanisms behind the acceleration of cosmic rays up to the highest observed energies.



R É S U M É

Voici presque un demi-siècle, Greisen, Zatsepin et Kuz'min (GZK) prédisaient, à des énergies d'environ $10^{20}$ eV, une « fin d'origine cosmologique » du spectre des rayons cosmiques en raison de leurs interactions avec le fond diffus cosmologique le long de leur parcours depuis des sources extragalactiques lointaines. La suppression du flux au-delà de $4 \times 10^{19}$ eV est aujourd'hui confirmée ; cependant, les données actuelles sont insuffisantes pour conclure quant à son origine. Est-elle due à une perte d'énergie lors de la propagation ? À la puissance limitée des accélérateurs astrophysiques ? Ou bien à une combinaison des propriétés des sources et des effets de propagation ? Nous présentons les relations entre l'infléchissement spectral observé et la composition des rayons cosmiques, les propriétés de leurs sources et la présence de champs magnétiques. Nous discutons des informations complémentaires nécessaires pour conclure sans ambiguïté quant à l'origine de la suppression du flux et aux mécanismes à l'origine de l'accélération des rayons cosmiques aux énergies les plus élevées observées.

© 2014 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

*E-mail address:* harari@cab.cnea.gov.ar.

http://dx.doi.org/10.1016/j.crhy.2014.02.011
1631-0705/

Please cite this article in press as: D. Harari, The flux suppression at the highest energies, C. R. Physique (2014), http://dx.doi.org/10.1016/j.crhy.2014.02.011

## 1. Introduction

The existence of about 400 photons with median energy $6 \times 10^{-4}$ eV in each cubic centimeter everywhere throughout the Universe has a strong impact upon the propagation of cosmic rays with energy around 23 orders of magnitude larger. This was first noted by Greisen [1] and independently by Zatsepin and Kuz'min [2], soon after the discovery of the cosmic microwave background (CMB) [3]. They realized that protons with energy around and above $6 \times 10^{19}$ eV can produce pions in their collisions with the CMB photons, and estimated the timescale for energy loss to be several hundred times smaller than the expansion time of the Universe. This led them to predict a "cosmologically meaningful termination" of the spectrum of cosmic rays (CRs). If the sources are uniformly distributed across the Universe, the "GZK effect" implies a strong flux suppression. Only a relatively small local neighborhood (in cosmological terms) contributes significantly to the flux of protons that arrive at Earth with energy above the threshold for pion-photoproduction, while the entire Hubble volume fills up the flux at lower energies. Even the one event recorded with the Volcano Ranch array [4] at $10^{20}$ eV three years before the GZK prediction appeared surprising. A strong flux suppression was also predicted if the cosmic rays were heavier nuclei instead of protons, since photodisintegration also occurs above a comparable energy threshold over cosmologically short timescales.

Forty-two years after the GZK prediction, the High Resolution Fly's Eye experiment (HiRes) [5] and the Pierre Auger Observatory [6] independently measured a suppression of the flux of cosmic rays above $4 \times 10^{19}$ eV compatible with a "cosmologically meaningful termination". The efforts to improve accuracy and exposure to a flux at the level of 1 particle per km$^2$ per century were largely driven by results from the AGASA Observatory, that gave unconfirmed evidence for trans-GZK particles [7]. Updated results from Auger [8] indicate that at $4 \times 10^{19}$ eV the flux is half of what would be expected with a power-law extrapolation from smaller energies, and the significance with which the suppression is confirmed is more than $20\sigma$. The Telescope Array (TA) [9,10] has now added independent confirmation of the suppression. The features observed by the different experiments are compatible within their systematic uncertainties [11].

In this article we will first summarize some aspects of the GZK effect. Then we will argue that, striking as it may be that the observed suppression matches the features predicted almost half a century ago, the physical origin of the suppression remains uncertain. The spectral steepening depends upon a variety of yet poorly constrained parameters, such as the CR composition, the nature and distribution of the sources, the range of maximum energy to which they can accelerate CRs, the sources spectral index and evolution, and the amount of diffusion across intervening magnetic fields. Current data are insufficient to conclude whether the flux is suppressed due to an energy-loss propagation effect, or else because astrophysical accelerators reach their maximum power at energies comparable to the GZK threshold, or indeed to a combination of both source physical properties and propagation effects. Degeneracy in the parameter space may prevent the resolution of this puzzle with measurements of the spectral shape alone.

## 2. The GZK horizon for protons and nuclei

In the rest frame of a proton with energy around $10^{20}$ eV, most incoming CMB photons have energies above 150 MeV, sufficient to produce the $\Delta^+$ resonance, that decays to a neutron and a $\pi^+$ or to a proton and a $\pi^0$:

$$\mathrm{p} + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow \mathrm{p} + \pi^0 \quad \text{or} \quad n + \pi^+. \tag{1}$$

An order of magnitude estimate of the energy attenuation length can be obtained by approximating the interaction cross-section to be $\sigma \approx 10^{-28}$ cm$^2$ and that there are about 400 CMB photons per cubic centimeter, which leads to a mean free path of the order of 10 Mpc. Since a proton loses on average 20% of its energy in each interaction, its energy will decrease by an order of magnitude after traversing 100 Mpc. Taking into account the spectral distribution of CMB photons, the effective threshold for the GZK effect is actually lower, of the order of $3 \times 10^{19}$ eV. The energy of the protons is also attenuated by $\mathrm{e}^+\mathrm{e}^-$ pair production, a process that becomes dominant at lower energies. The energy is also adiabatically red-shifted, a process that becomes relevant over cosmological travel times. Detailed calculations must also account for the spectral distribution and redshift of the CMB photons. The interaction with the infrared extragalactic background light can be neglected in the case of protons, but not for heavy nuclei, that lose energy in photodisintegration processes. When the center of mass energy exceeds the giant dipole resonance, nucleons can be emitted. Less energy is required in the center of mass, as compared to pion-photoproduction, and both the CMB and infrared photons are relevant targets.

After the first initial estimates and predictions by Greisen and by Zatsepin and Kuz'min, several detailed calculations of energy loss due to propagation effects across the universal photon fields were performed, both for protons (e.g., [12–24]) as well as for heavier nuclei (e.g., [25–35]). Some recent reviews are [36–38]. Public codes are available [39,40] to realistically simulate CR propagation taking into account all relevant particle interactions, tools that become more necessary to discriminate between alternative scenarios as the measurements improve.

Here we will illustrate some generic features of the GZK effect following the calculations in [31]. Fig. 1 displays the results for the energy attenuation length for protons (left) and for nuclei (right). Energy loss processes limit the distance from which a source can contribute significantly to the flux at Earth. The size of the "GZK horizon" is estimated as follows. Under a continuous energy loss approximation, particles are assumed to be injected with an input spectrum $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha}$, and an attenuation factor is evaluated, given by the fraction of the events injected with energy above $E_{\mathrm{th}}$ which still remain