Should One Really Expect a GZK Cutoff?

Etienne Parizot,[1] Olivier Deligny,[2] and Antoine Letessier-Selvon[2]
(1) IPN Orsay, CNRS/Univ. Paris-Sud, bât. 100, 91406 Orsay Cedex, France
(2) LPNHE, Universités de Paris 6 et 7, CNRS, 4 place Jussieu T33 RdC, F-75252 Paris Cedex 05, France

Abstract

We investigate the effect of a random extragalactic magnetic field on the propagation of charged particles above 10^{18} eV, and show that for field values in the 100nG range, the transition between the diffusive and ballistic regimes occurs in the same energy range as the GZK cutoff (a few 10^{19} eV). The interpretation of the latter as a decrease in the flux due to the sudden reduction of the visible horizon is therefore modified. Moreover, the size of the sphere of diffusion of a continuous cosmic-ray source being of the order of 10 Mpc, the local structure of the universe and therefore of potential astrophysical sources plays a dominant role in the expected flux. Under reasonable assumptions on the sources configuration, the expected GZK cutoff may even disappear.

1. Introduction

The cosmic microwave background (CMB) is expected to limit the travel distance of nucleons and nuclei above a few 10^{19} eV, due to photo-disintegration or photo-production of pions. These interactions induce a cut-off in the UHECR spectrum, known as the GZK cutoff, whose standard interpretation is that the flux should be significantly reduced above 100 EeV as a consequence of the sudden reduction of the visible universe – from a few Gpc below 10 EeV to less than 20 Mpc above a few 100 EeV. This simple view may however be strongly modified in the presence of extragalactic magnetic fields of the order of 0.1 μG. Such strong fields are compatible with current observations and upper limits from Faraday rotation measurements which indicate field strengths at the μG level within the central Mpc region of galaxy clusters.

In intergalactic magnetic fields around 0.1 μG, 10 EeV protons have Larmor radii of 100 kpc and propagate diffusively between galaxies, while at higher energies (say above 100 EeV) the trajectories are essentially ballistic. The clear GZK cutoff picture may thus be blurred by another effect taking place in the same energy range: the transition between ballistic and diffusive transport regimes.

In addition, in such fields the radius of the diffusion sphere of a source

pp. 647–650

emitting since a few Gyr (corresponding to the attenuation time of 10^{18} eV protons, say) is about 10 Mpc. On this scale, the Universe is known to be neither isotropic nor uniform. This indicates that the local distribution of matter will play a dominant role in the observed energy spectra. It is thus tempting to imagine a scenario where a few local sources would dominate the observed UHECR fluxes at all energies: they would be sufficiently far away so that we lie outside their low-energy (1–10 EeV) diffusion spheres but close enough so that their high energy component does not get significantly attenuated.

2. Proton transport and energy spectrum

We simulate a magnetized universe following the method of ref. [1], with a purely turbulent field with Gaussian fluctuations and a power law spectrum ($(\delta\bar{B}(\vec{k})^2 = S_0 k^{-2-\beta}$, with the Kolmogorov value $\beta = 5/3$) between the $k_{\max}$ and $k_{\min}$ given by the coherence length of our field model, 1 Mpc, and a grid size of 15 kpc. We then perform Monte-Carlo simulations of the propagation of protons: at each step along their trajectory we solve the equation of motion in the local field and compute the energy loss due to pion photo-production, simulating each interaction. The losses due to pair production are treated continuously. Neutrons, if produced, are also followed until they transform again into a proton via the photo-production of pions or until they decay.

To compute the spectrum of a source at a given distance R from the observer, we first generate a set of protons at the origin and record the times and the energies at which they cross a sphere of radius R, centered on the origin. We thus obtain the distribution of proton energies as a function of trajectory length, for various distances of the observer and various initial energies of the protons (see [2] for details). From this, we are then able to compute the probability $\mathcal{F}(t - t_0, E; R, E_0)\mathrm{d}E\mathrm{d}t$ for a particle produced at time t_0 with energy E_0 to be detected at a given distance R at time t with an energy E, and assuming an isotropic distribution of sources $\rho(R)$, we obtain the spectrum observed today (time t) from sources located between R_{min} and R_{max}, with an injection spectrum $f(E_0)$, as:

$$\frac{\mathrm{d}N}{\mathrm{d}E}(t) = \int_{R_{min}}^{R_{max}} \mathrm{d}V \int_0^t \mathrm{d}t_0 \int_{E_0^{min}}^{E_0^{max}} \mathrm{d}E_0 f(E_0) \frac{1}{4\pi R^2} \mathcal{F}(t - t_0, E; R, E_0). \qquad (1)$$

3. Energy coincidences and magnetic horizon

At low enough energy, where protons do not lose much energy and propagate diffusively, the radius of the diffusion sphere as a function of time and energy is roughly given by $R(E,t) \sim \sqrt{4D(E)t}$, where $D(E)$ is the diffusion coefficient derived from proton transport simulations. For a given source distance, R, the energy scale separating ballistic and diffusive regimes can be estimated by com-

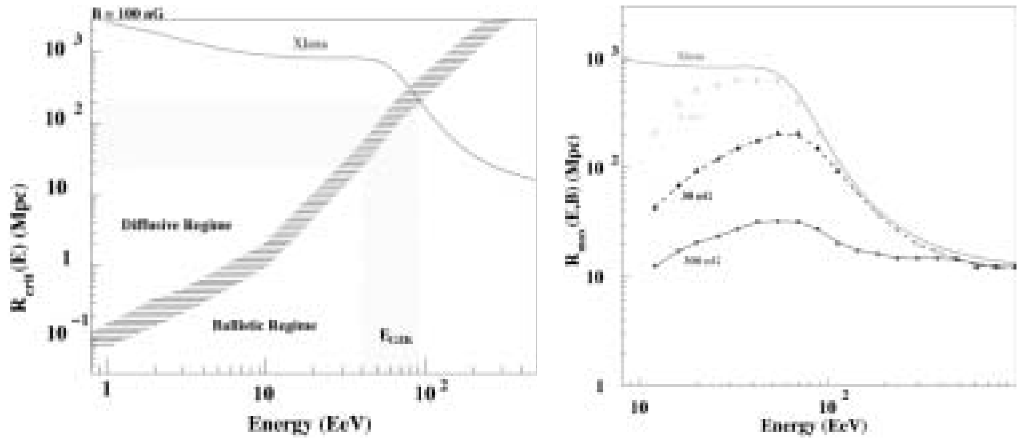

Fig. 1. a: Length scale where the transition between diffusive and ballistic regimes occurs, as a function of energy, for a 100 nG field; b: Magnetic horizon as a function of energy and for various field strengths, defined as the radius of the sphere enclosing 68% of the particles trajectories for a propagation time equal to the energy loss time (top solid line).

paring the corresponding propagation times: $R^2/4D(E_\mathrm{c})$ and R/c. Fig. 1a shows this energy as a function of source distance for a random field of $0.1\,\mu$G. It is remarkable that for sources within the GZK sphere (10–100 Mpc), the transition occurs around the GZK energy (i.e. a few tens of EeV). This is a mere, but important coincidence, depending on the pion mass, the temperature of the CMB and the value of reasonable intergalactic magnetic fields.

One can also introduce the concept of *magnetic horizon*, beyond which we can no longer see the sources. Using the Monte Carlo described above, we computed its radius as the maximum distance reached by 68% of the particles during a propagation time $T_{loss} = E/\dot{E}$. It goes from $\sim \sqrt{4D(E)T_{loss}(E)}$, in the diffusive regime, up to the GZK distance at high energy. It is shown on Fig. 1b.

4. Results and conclusion

We have computed the observed spectra for continuous sources with power-law injection spectra of index 2.3 up to $E_\mathrm{max} = 1000$ EeV, for 45 values of the source distance between 1 Mpc and 1 Gpc, and for turbulent field values ranging from 3 to 300 nG. Some of them are compared on Fig. 2a. The spectrum of a very nearby source (1 Mpc) shows a softening (index changing form -2.3 to about -3.0) at low energies due to the accumulation of low energy particles, while at high energy the original spectrum is restored. There is no GZK cutoff, of course, but such a nearby source would lead to a strongly anisotropic flux, incompatible with current data.

For a source at 10 Mpc, the flux is only slightly reduced at high energy and the contributions (after the usual correction by E^3) at 10^{19} eV and 10^{21} eV

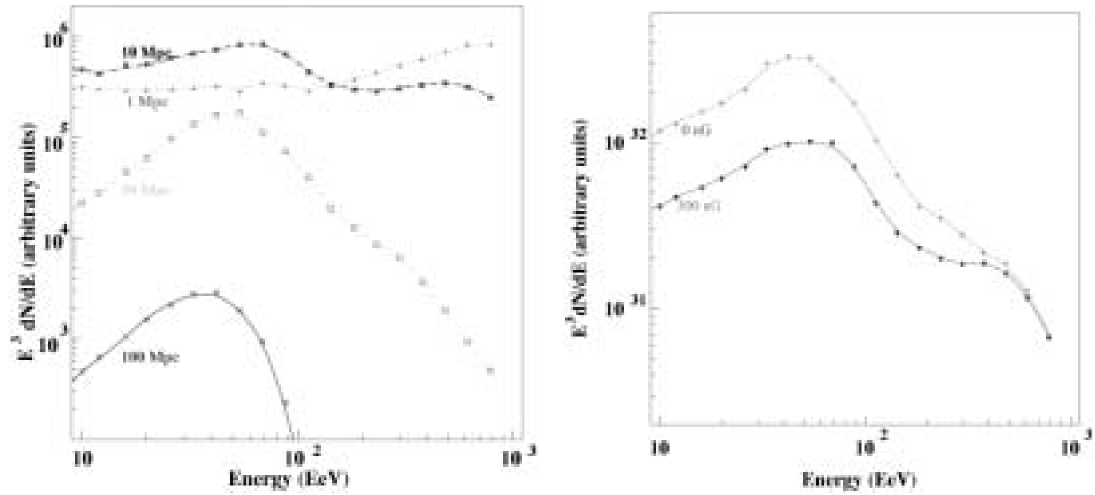

Fig. 2. a: UHECR spectra of sources at 1 (+), 10 (*), 50 (o) and 100 (x) Mpc in a turbulent field of 100nG, normalized so that the fluxes would be identical without magnetic field and energy losses; b: Attenuation of the GZK cutoff by magnetic fields: a uniform distribution of sources between 10 and 1000 Mpc has been assumed, with and without magnetic fields.

are roughly the same, leading to a nearly flat UHECR spectrum (E^{-3}).

For larger distances, the flux is strongly attenuated at high energy (standard GZK cutoff), *but also at low energy* because of the diffusive regime: UHE protons have not been able to reach us!

The main conclusion of this study is that far away sources have a negligible contribution to the total flux at *all* energies. The presence of random magnetic fields thus modifies the weight of the sources contributing to the observed flux. In Fig. 2b we compare the spectrum obtained from a uniform distribution of sources between 10 Mpc and 1 Gpc, with and without a 300 nG random field. In the later case, the flux reduction at low energy is clearly visible, as the observer lies mostly outside the diffusion spheres. The exact form of the spectrum strongly depends on the source configuration on a scale of a few tens of Mpc, where the universe happens to be highly non uniform (another coincidence!). Therefore the local source configuration may lead to a spectrum that lies anywhere between the shapes of those obtained from individual sources at 10 or 50 Mpc as shown on Fig. 2a, i.e. in particular with no GZK cutoff! (NB: for details, comments and references, please see [2].)

1. Casse F., Lemoine M., Pelletier G. 2002, Phys.Rev. D65, 023002 (astro-ph/0109223); Casse F., *Thèse de doctorat*, Université de Grenoble, 2001
2. Deligny O., Letessier-Selvon A., Parizot E. 2003, submitted to Astropart. Phys. (astro-ph/0303624)