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GZK Photons in the Ultra High Energy Cosmic Rays.*

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We calculate the flux of "GZK- photons", namely the flux of Ultra High Energy Cosmic Rays (UHECR) consisting of photons produced by extragalactic protons through the resonant photoproduction of pions, the so called Greisen-Zatsepin-Kuzmin (GZK) effect. We show that if the UHECR are mostly protons, depending on the slope of the proton flux, distribution of sources and intervening backgrounds, between 0.01% and 5% of the UHECR above 10^{19} eV are photons. Detection of these photons will open new window for UHECR gamma-ray astronomy. Detection of a larger photon flux would imply the emission of photons at the source or new physics.

1. Introduction

The cosmic rays with energies beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2] at 4×10^{19} eV present a challenging outstanding puzzle in astroparticle physics [3, 4]. Nucleons with energies above 10^{20} eV could not reach Earth from a distance beyond 50 to 100 Mpc because they scatter off the cosmic microwave background (CMB) photons with a resonant photoproduction of pions [2]. From the decay of $\pi^{\pm}$ one obtains neutrinos. These "GZK neutrinos" have been extensively studied, from 1969 [5] onward. From the decay of π^0 we obtain photons, "GZK photons", with about 0.1 of the original proton energy, which have been known to be a subdominant component of the UHECR since the work of Wdowczyk *et al.* in the early 1970's [6]. In 1990 it was suggested that if the extragalactic radio background and magnetic fields are small ($B < 3 \times 10^{-11}$ G) GZK photons could dominate over protons and explain the super-GZK events [7]. The dependence of the GZK photon flux on extragalactic magnetic fields was later studied in Ref. [8]. The argument of Ref. [7] and its dependence on extragalactic magnetic fields was again discussed [9] in connection with the possible correlation of UHECR arrival directions with BL Lacertae objects. In this talk I present results of recent paper [1] where we show that if the UHECR are mostly protons, depending on the UHECR spectrum assumed, the slope of the proton flux, distribution of sources and intervening backgrounds, between 10^{-4} and 5×10^{-2} of the UHECR above 10^{19} eV and between 10^{-5} and 0.6 of the UHECR above 10^{20} eV are GZK photons, the range being much higher for the AGASA spectrum than for the HiRes spectrum (see Fig. 3).

2. The GZK photon flux

The resulting GZK photon flux depends on several astrophysical parameters. These parametrize the initial proton flux, the distribution of sources, the radio background and the EGMF. With respect to cosmological parameters, we take the Hubble constant $H = 70$ km s^{-1} Mpc^{-1}, a dark energy density (in units of the critical density) $\Omega_\Lambda = 0.7$ and a dark matter density $\Omega_{\rm m} = 0.3$. We assume the sources extend to a maximum redshift $z_{\rm max} = 2$ (although any $z_{\rm max} > 1$ gives the same results at the high energies we consider) and disregard a possible evolution of the sources with redshift.

*In this talk I'm presenting results of our common work with G.Gelmini and O.Kalashev [1].

We parametrize the initial proton flux for any source with the following power law function,

$$F(E) = f\,\frac{1}{E^{\alpha}}\,\theta(E_{\max} - E)\;. \tag{1}$$

The power law index α and maximum energy $E_{\max}$ are considered free parameters. The amplitude f is fixed by normalizing the final proton flux from all sources to the observed flux of UHECR, which we take to be either the AGASA flux or the HiRes flux.

We use the 18 highest energy data bins of AGASA and the 16 highest energy data bins of HiRes-1 monocular data. We also separately check the χ^2 for the AGASA events above the GZK cutoff, i.e. for the 3 highest energy AGASA data bins, with $E > 10^{20}$ eV. Additionally, we check that the number of events predicted above the end point of the AGASA spectrum (the energy above which AGASA has observed no events), i.e. at $E > 2.5 \times 10^{20}$ eV, is not larger than 4 (predicting 4 events and observing none has a very small Poisson probability of 1.8%). The number of events we predict above the end point of the HiRes spectrum, at $E > 3.2 \times 10^{20}$ eV, is always much smaller than 4.

To fit data at low energies we introduce low energy component (LEC) which can consist of Galactic or/and extragalactic nuclei and protons with spectrum which dominate below GZK cutoff and negligible above it. We also parametrize the with

$$F_{\rm LEC} \sim E^{-\beta}\exp(-E/E_{\rm cut})\;. \tag{2}$$

and we fit the amplitude to the lowest energy bin in the figures. We choose the parameter $\beta = 2.7 - 2.8$ to fit the low energy spectral points, and the parameter $E_{\rm cut}$ so that the minimum χ^2 value per degree of freedom of the fit is smaller than one.

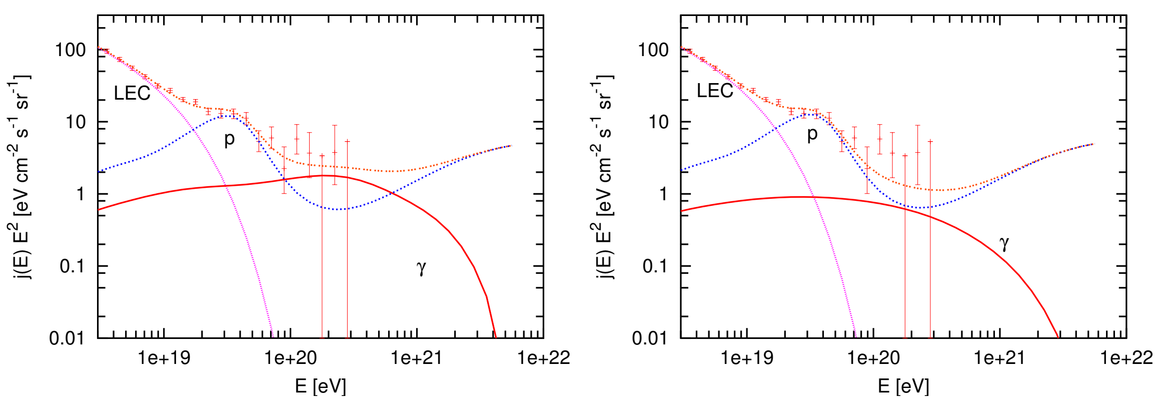

Figure 1. Example of a fit to the AGASA data (with extragalactic protons, the GZK photons they produce and a low energy component (LEC) at $E < 10^{19}$ eV. . Here we try to **maximize** (left) and **minimize** (right) the photon component, still having good fit to AGASA. We take an extragalactic proton spectrum $\sim 1/E$ with maximum energy $E_{\max} = 10^{22}$ eV, $B_{\rm EGMF} = 10^{-11}$ G and vary the radio background from minimum (left) to middle (right) values.

The fit to the super-GZK AGASA events in Fig. 1a is now perfect, due to the GZK photons: it has a minimum $\chi^2 = 2.6$ for 3 degrees of freedom and at $E > 10^{20}$ eV there are 11.5 events (6.8 photons and 4.5 protons) where AGASA has observed 11. The spectrum predicts 4 events (2 photons and 2 protons) at energies above $2.5{\times}10^{20}$ eV, where AGASA has seen none, which we take as acceptable (the probability is small, 1.8%). Larger $E_{\max}$ or lower α values would lead to predict even more events where AGASA has seen none and would therefore not fit well the AGASA spectrum any longer.

The fit to the super-GZK AGASA events in Fig. 1b, where we try to lower the GZK flux, is not as good as that in Fig. 1a: it has a minimum $\chi^2 = 5.5$ for 3 degrees of freedom and at $E > 10^{20}$ eV there are 7 events (2.5 photons and 4.5 protons). But, this fit is better than that is Fig. 1a above the end-point of the AGASA spectrum: it predict only 2.7 events above the highest energy AGASA point, which has a 6.7% Poisson probability.

As we see, a good fit to the AGASA data at $E > 10^{20}$ eV with GZK photons is strongly restricted by the total number of events on one side and by the number of events above the end-point of the AGASA spectrum on the other. Thus, Figs. 1a-b provide an estimate of the maximum and minimum GZK photon flux which fit the AGASA data.

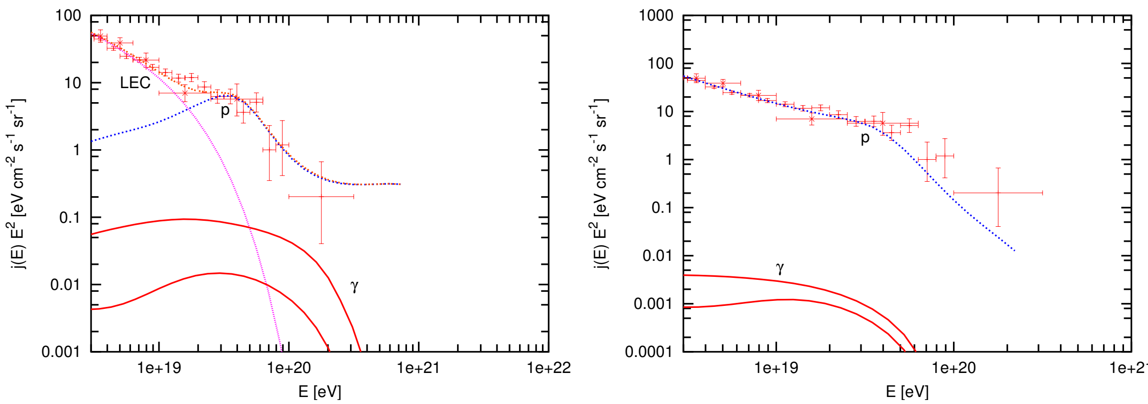

Figure 2. Example of a fit to the HiRes data with LEC, GZK photons and protons and with only protons (right). we try to **maximize** (left) and **minimize** (right) the photon component, still having good fit to HiRes. component.

In Figs. 2a-b we present two fits to the HiRes data, maximizing and minimizing the GZK photon flux. In Fig. 2a we assume an extragalactic proton spectrum $\sim 1/E$ with maximum energy $E_{\rm max} = 10^{21}$ eV minimum radio background and $B_{\rm EGMF} = 10^{-11}$ G for the higher photon curve (maximum radio background and $B_{\rm EGMF} = 10^{-9}$ G for the lower photon curve). In Fig. 2b we fit the HiRes data with a conservative model with a soft extragalactic proton spectrum, which does not require a low energy component. We take $\alpha = 2.7$ and the smallest cutoff energy which provides a good fit, which is $E_{\rm max} = 3 \times 10^{20}$ eV.

3. Discussion.

Fig. 3 shows the fraction of photons as percentage of the total predicted integrated UHECR flux above the energy E for model fits to AGASA (left) and HiRes (right) UHECR spectrum. We prefer to give the ratio of photons over total UHECR events, instead of the sometimes used ratio of photons over nucleon, because of the possibility that part of the UHECR consists of particles other than photons and nucleons, such as heavy nuclei.

The predictions of the Top-Down models we considered almost saturate the present upper limit of $N_\gamma/N_{\rm tot} < 50\%$ obtained from AGASA data [12] at 10^{20} eV. So, either UHECR photons at energies close to 10^{20} eV will be detected, or better experimental limits will be obtained in the future by Auger or HiRes. An upper limit close to 10% at those energies, would reject all Top-Down models. If the UHECR spectrum is similar to that of AGASA, this limit would also reject the possibility of explaining the spectrum at $E > 10^{20}$ eV with extragalactic protons plus GZK photons.

We have shown in this paper that either the detection of UHECR photons or an improvement of the existing

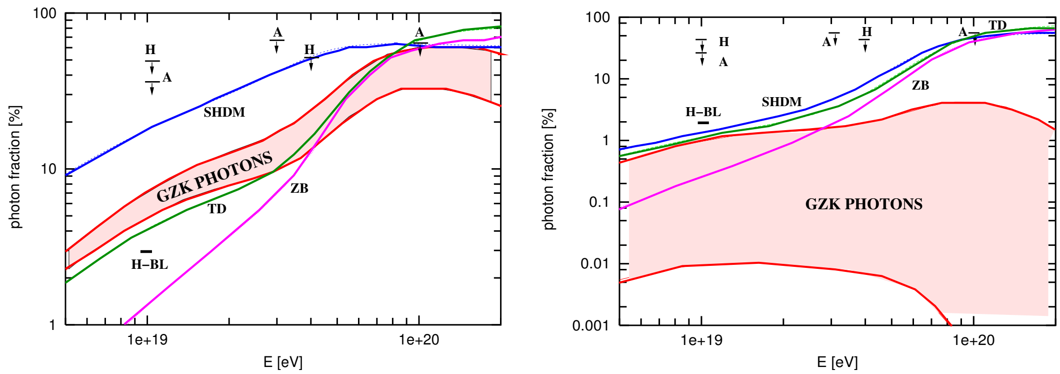

Figure 3. Photon fraction in percentage of the total predicted integrated UHECR spectrum above the energy E for (a) the AGASA spectrum (left panel) and (b) the HiRes spectrum (right panel). The pink region show the range of GZK photon fractions expected if only nucleons are produced at the sources. The curves labeled ZB (Z-bursts), TD (topological defects) and SHDM (Super Heavy Dark Matter model) show examples of minimum photon fractions predicted by these models. Upper limits: **A** from AGASA, Ref. [10] at $1 - 3 \times 10^{19}$ eV, and obtained with AGASA data at 10^{20} eV [12]; **H** from Haverah Park [11]; **H-BL** show the fraction of HiRes stereo events required to explain a correlation with BL Lac sources [13].

upper limits on the photon flux, is very important, both for Top-Down as well as for Bottom-Up mechanisms to explain the UHECR. The photon ratio at 10^{20} eV is crucial test for Top-Down models. With astrophysical sources, the GZK photon flux is important to understand the initial proton or neutron spectrum emitted at the UHECR sources and the distribution of sources. UHECR photons may help us to understand the intervening extragalactic magnetic fields and radio background. We have presented fits to both the AGASA and the HiRes UHECR spectra with extragalactic nucleons, the GZK photons they produce and, when needed, an additional low energy component at energies below 10^{19} eV. The band of expected GZK photon flux depends clearly on the UHECR spectrum (see Fig. 3a compared to Fig. 3b). The detection of UHECR photons would open a new window for ultra-high energy astronomy and help establish the UHECR sources.

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