GZK photons as UHECR above $10^{19}$ eV

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Abstract. “GZK photons” are produced by extragalactic nucleons through the resonant photoproduction of pions. We present the expected range of the GZK photon fraction of UHECR, assuming a particular UHECR spectrum and primary nucleons, and compare it with the minimal photon fraction predicted by Top-Down models.

The Pierre Auger Observatory [1] may prove photon fractions in the Ultra-High Energy Cosmic Rays (UHECR) above $10^{19}$ eV at the level of 10% (maybe even a few%). Based on Ref. [2], here we will address the physical implications of such detection or limit. In particular, we will discuss if “GZK photons” could be observed at this level or, otherwise, if limits on the parameters on which their flux depends could be obtained from the non observation of photons at this level. We call “GZK photons” those photons produced by extragalactic nucleons through the resonant photoproduction of pions, the so called GZK effect. In Ref. [2] we fitted the assumed UHECR spectrum above $2 \times 10^{19}$ eV solely with primary nucleons and the GZK photons they produce. The GZK photon flux depends on the UHECR spectrum assumed, the slope and maximum energy of the primary nucleon spectrum, the minimum distance to the sources and the intervening radio background and average extragalactic magnetic field. We took a phenomenological approach in choosing the range of the several relevant parameters, namely we took for each of them a range of values mentioned in the literature, without attempting to assign them to particular sources or acceleration mechanisms. We also assumed the existence of a galactic or extragalactic Low Energy Component (LEC) when necessary to fit the assumed UHECR at energies below $10^{19}$ eV, taking care that it is negligible at energies $3\times10^{19}$ eV and above.

We used a numerical code developed in Ref. [3] to compute the flux of GZK photons produced by an homogeneous distribution of sources emitting originally only protons (however the results at the high energies considered is the same for primary neutrons). It uses the kinematic equation approach and calculates the propagation of nucleons, stable leptons and photons using the standard dominant processes.

We parametrized the initial proton flux for any source with a power law function, $F(E) = f E^{-\alpha} \theta(E_{\text{max}} - E)$. The power law index $\alpha$ and maximum energy $E_{\text{max}}$ were considered free parameters. The amplitude $f$ was fixed by normalizing the final proton flux from all sources to the observed flux of UHECR, which we took to be either the AGASA spectrum or the HiRes spectrum (given that a reliable Auger spectrum in not yet available). We considered the power law index to be in the range $1 \leq \alpha \leq 2.7$ and $E_{\text{max}}$ between $10^{20}$ eV and $10^{22}$ eV. For the average extragalactic magnetic field we took the range $10^{-11}$G to $10^{-9}$G, [4] and for the radio background we considered three estimates: one from Clark et al and two higher ones from Protheroe and Biermann [5].

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The largest GZK photon fractions in UHECR happen for small values of $\alpha$, large values of $E_{\text{max}}$, small minimal distance to the sources (which is compatible with a small frequency of clustering of the events) and small intervening backgrounds. The smallest GZK photon fluxes are obtained with the opposite choices. In the most favorable cases for a large photon flux, GZK photons could dominate the UHECR flux in an energy range above $10^{20}$ eV. This allowed us [2] to fit the AGASA data, at the expense of assuming that the initial protons could have a hard spectrum $\sim 1/E$ and be accelerated to energies as high as $10^{22}$ eV. In this extreme case, the AGASA data can be explained without any new physics, except in what the mechanism of acceleration of the initial protons is concerned. With the HiRes spectrum the GZK photons are always subdominant and can be neglected for the fit.

Proceeding in this manner, in Ref. [2] we fitted the AGASA [6] and the HiRes monocular [7] data trying to minimize and to maximize the number of GZK protons produced, to obtain the expected range of the GZK-photon fraction in UHECR. We found (see the pink bands in Fig. 1) that the GZK photon fraction of the total integrated UHECR flux, for the AGASA spectrum is between 5% and 7% above $10^{19}$ eV and between 30% and 60% above $10^{20}$ eV, thus Auger should be able to see these photons or place interesting bounds on the flux parameters. Recall that fitting the AGASA data with astrophysical sources requires the extreme choices for the initial spectrum mentioned above. With the HiRes spectrum, instead the predicted GZK photon fraction is between 0.01% and 1% of the UHECR above $10^{19}$ eV and between 0.001% and 4% above $10^{20}$ eV, thus these photons may or may not be within the reach of Auger.

![Figure 1](image.png)

**Figure 1.** 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 regions 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- necklaces) and SHDM (Super Heavy Dark Matter model) show examples of minimum photon fractions predicted by these models. Upper limits: A from AGASA, Ref. [8] at $1 - 3 \times 10^{19}$ eV, and, Ref [9], obtained with AGASA data at $10^{20}$ eV; H from Haverah Park [10]; H-BL show the fraction of HiRes stereo events required to explain a correlation with BL Lac sources [11].

Detection of these GZK photons would open the way for UHECR photon astronomy. Detection of a larger photon flux than expected for GZK photons given the particular UHECR spectrum assumed, would imply the emission of photons at the source or new physics. New physics is involved in Top-Down models, proposed as an alternative to acceleration models to explain the origin of the highest energy cosmic rays. All Top-Down models predict photon dominance at the highest energies (and no heavy nuclei). In Ref. [2], we estimated the minimum photon fraction Top-Down models predict, not only assuming the AGASA spectrum, which
these models were originally proposed to explain, but also assuming the HiRes spectrum. We showed that at high energy, close to $10^{20}$ eV, the maximum expected flux of GZK photons is comparable to (for the AGASA spectrum) or much smaller than (for the HiRes spectrum) the minimum flux of photons predicted by Top-Down models which fit the AGASA or the HiRes data (see Fig. 1). Three Top-Down models were considered: Z-bursts [12], topological defects (necklaces) (for a review see for example Ref. [13]) and super heavy dark matter particles [14] (in particular, predictions of Ref. [15] were used).

In order to estimate the minimum photon ratio predicted by Top-Down models we assumed that these models explain only the highest energy UHECR (if they do not explain even those events, the models are irrelevant for UHECR). For this purpose we made liberal use of a component of extragalactic nucleons which would explain all but the highest energy UHECR. The assumption of two components, one of accelerated nucleons and another of Top-Down generated particles, which would conspire to produce a continuous spectrum, is contrived, and was used only as a means to minimize the number of Top-Down photons. Fitting the AGASA and HiRes UHECR spectra in this manner we showed that the photon ratio at energies close to $10^{20}$ eV is always larger than 10%, in most cases is larger than 50%, independently of the UHECR spectrum assumed, making this is a crucial test for Top-Down models. Reaching the level of $\sim 30\%$ ($10\%$) on the photon ratio at energies close to $10^{20}$ eV, Auger will find UHECR photons or reject most (all) Top-Down models, independently of the UHECR spectrum.

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