GZK Photons in the Minimal Ultra High Energy Cosmic Rays Model

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Abstract

In a recently proposed model the cosmic rays spectrum at energies above $10^{18}$ eV can be fitted with a minimal number of unknown parameters assuming that the extragalactic cosmic rays are only protons with a power law source spectrum $\sim E^{-\alpha}$ and $\alpha \approx 2.6$ [1]. Within this minimal model, after fitting the observed HiRes spectrum with four parameters (proton injection spectrum power law index and maximum energy, minimum distance to sources and evolution parameter) we compute the flux of ultra-high energy photons due to photon-pion production, the GZK photons, for several radio background models and average extragalactic magnetic fields with amplitude between $10^{-11}$ G and $10^{-9}$ G. We find the photon fraction to be between $10^{-4}$ and $10^{-3}$ in cosmic rays at energies above $10^{19}$ eV. These small fluxes could only be detected in future experiments like Auger North plus South and EUSO.

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1 Introduction

The sources and the composition of the Ultra High Energy Cosmic Rays (UHECR), namely the cosmic rays with energy $E > 10^{18}$ eV, are still unknown. The highest energy cosmic rays, above $\sim 1 \times 10^{19}$ eV, are likely of extragalactic origin, since they could not be confined by the galactic magnetic fields. Low energy cosmic rays originate within our galaxy. Two different proposals have been made for the possible transition from galactic to extragalactic cosmic rays in the spectrum. Historically the “ankle”, a feature close to $1 \times 10^{19}$ eV, was interpreted as the transition from a rapidly falling galactic flux component to a flatter spectrum of extragalactic origin subdominant.
at lower energies. Alternatively, the “ankle” feature can be interpreted as an absorption “dip” at energies $E = 3 - 10$ EeV [1], due to the propagation of extragalactic protons over large distances in the cosmic microwave background (CMB) [2]. The transition from a galactic to extragalactic cosmic rays would then happen at lower energies, $\sim 1 \times 10^{18}$ eV or below. This would agree with the indication of a transition from heavy to light primary nuclei observed by the HiRes collaboration at energies close to $5 \times 10^{17}$ eV [3]. In this case the UHECR HiRes spectrum [4,5], in which the GZK cutoff [6] is present, can be fitted with a minimal number of unknown parameters assuming the extragalactic cosmic rays are only protons with a power law source spectrum $\sim E^{-\alpha}$ with $\alpha \approx 2.6$ [1]. This is the minimal UHECR model we study in this paper.

Let us mention that the Fermi acceleration process predicts lower values of power law index $\alpha \approx 2.2$, which are compatible with the minimal UHECR model if a power law distribution of the maximum source energies is assumed [7]. Here we do not study this possibility.

The GZK process produces pions. From the decay of $\pi^\pm$ one obtains neutrinos, the “cosmogenic neutrinos” [8]. From the decay of $\pi^0$ we obtain photons, which we call “GZK photons”. Previously we studied in detail the GZK photon flux dependence on different unknown parameters of the assumed source spectrum and distribution and the intervening cosmological backgrounds [9]. Here we discuss the perspectives for photon detection in the minimal UHECR model. Our previous results of Ref. [9] show that because of the relatively hard source spectrum required, with $\alpha \approx 2.6$, the GZK photons are subdominant at all energies.

The plan of the paper is the following. In the next section we explain our calculations. In Section 3 we study the range of parameters of the source spectrum and distribution that best fit the UHECR spectrum, which is dominated by proton primaries at all energies. In Section 4 we show the maximum and minimum expected level of GZK photons and comment briefly on cosmogenic neutrinos. Our conclusions follow in Section 5.

## 2 Propagation of protons and photons

We use a numerical code originally developed in Ref. [10] to compute the flux of GZK photons produced by a homogeneous distribution of sources emitting originally only protons. This is the same numerical code as in Ref. [9], with a few modifications. This code was compared at the individual reaction level with the code developed by G. Sigl and S. Lee [11] and was already used in several studies of cosmic ray and secondary gamma-ray and neutrino
fluxes \[12\].

The code uses the kinematic equation approach and calculates the propagation of nuclei, nucleons, stable leptons and photons using the standard dominant processes. For nucleons, it takes into account single and multiple pion production and \(e^\pm\) pair production on the CMB, infrared/optical and radio backgrounds, neutron \(\beta\)-decays and the expansion of the Universe. The hadronic interactions of nucleons are now derived from the well established SOPHIA event generator \[13\], more accurate in the multi-pion regime than the old code in Ref. \[10\]. For photons, the code includes \(e^\pm\) pair production, \(\gamma + \gamma_B \rightarrow e^+e^-\), double \(e^\pm\) pair production \(\gamma + \gamma_B \rightarrow e^+e^-e^+e^-\), processes. For electrons and positrons, it takes into account inverse Compton scattering, \(e^\pm + \gamma_B \rightarrow e^\pm\gamma\), triple pair production, \(e^\pm + \gamma_B \rightarrow e^+e^+e^-\), and synchrotron energy loss on extra galactic magnetic fields (EGMF). All these reactions are discussed in detail for example in the Ph.D. thesis of S.Lee \[11\] and that of O.Kalashev \[10\]. The propagation of nucleons and electron-photon cascades is calculated self-consistently. Namely, secondary (and higher generation) particles arising in all reactions are propagated alongside the primaries.

As it is usual, we take the spectrum of an individual UHECR source to be of the form:

\[
F(E) = \frac{f}{E^\alpha} \Theta(E_{\text{max}} - E)
\]  

(1)

where \(f\) provides the flux normalization, \(\alpha\) is spectral index and \(E_{\text{max}}\) is the maximum energy to which protons can be accelerated at the source.

We assume a standard cosmological model with a 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 \(\Omega_m = 0.3\). The total source density in this model can be defined by

\[
n(z) = n_0(1 + z)^{3+m}\Theta(z_{\text{max}} - z)\theta(z - z_{\text{min}}),
\]

(2)

where \(m\) parameterizes the source density evolution, in such a way that \(m = 0\) corresponds to non-evolving sources with constant density per comoving volume, and \(z_{\text{min}}\) and \(z_{\text{max}}\) are respectively the redshifts of the closest and most distant sources. Sources in the range \(2 < z < z_{\text{max}}\) have a negligible contribution to the UHECR flux above \(10^{18}\) eV. The value of \(z_{\text{min}}\) is connected to the density of sources and influences strongly the shape of the “bump” produced by the pile-up of protons which loose energy in the GZK cutoff and the strength of the GZK suppression \[14,15,16\]. In the following we fix \(z_{\text{max}} = 3\) and consider three values for \(z_{\text{min}}\), namely 0, 0.005 and 0.01 in Eq. (2).
The main energy loss mechanism for photons with $E > 10^{19}$ eV is pair production on the radio background (at lower energies pair production on the CMB is more important), possibly followed by synchrotron radiation of electrons and positrons. To take into account the effect of the intervening backgrounds, here we fit the UHECR data assuming either minimal intervening radio background (which we take to be the radio background of Clark et al. [17]) and extragalactic magnetic field $E_{\text{GMF}} B = 10^{-11}$ G or a maximal intervening background (for which we take the largest radio background of Pratheroe and Biermann [18]) and a $E_{\text{GMF}} B = 10^{-9}$ G, with many different source models. A difference with respect to older versions of our code is in the infrared/optical background assumed. We use now the model of Ref. [19]. In any event, this background is not very important for the production and absorption of GZK photons at high energies.

We consider then many different spectra resulting from changing the slope $\alpha$ and the maximum energy $E_{\text{max}}$ in Eq. 1 within the ranges $2.3 \leq \alpha \leq 2.9$ and $1.6 \times 10^{20} \text{eV} \leq E_{\text{max}} \leq 1.28 \times 10^{21} \text{eV}$ and the source evolution parameter $m$ in Eq. (2) within the range $-2 \leq m \leq 3$. Notice that $E_{\text{max}}$ cannot be smaller than the largest event energy, $1.6 \times 10^{20} \text{eV}$, observed by HiRes. We change these parameters in steps $\alpha_n = 2.3 + 0.05n$, with $n = 1$ to $12$, $E_{\text{max}_-\ell} = 1.6 \times 10^{20} \text{eV} \times 2^\ell$, with $\ell = 0$ to $6$, and $m_i = -2 + i$ with $i = 0$ to $5$.

For each one of the models so obtained we compute the predicted UHECR spectrum by summing up the contributions of protons plus GZK photons arriving to us from all sources. In general models we need to consider a larger range of spectral indices [20]. In the minimal UHECR model we study here instead, one fits the observed spectrum UHECR down to energies $E = 1 - 2 \text{EeV}$ with extragalactic protons, which requires a steeply falling source proton spectra with $\alpha \geq 2.3$. For such injected proton spectra the GZK photons reaching us are subdominant at all energies. So, fitting the observed HiRes data with the sum of protons and photons arriving to us from all sources is almost equivalent to using just the protons reaching us.

With the spectrum predicted for each combination of parameters we fit the UHECR data from $2 \times 10^{18}$ eV up to the end point of the HiRes spectrum (i.e. the 28 highest energy bins of the HiRes 1 and 2 combined monocular data) plus one extra bin at energies above the “end point” (the point in energy beyond which no events were observed) of the spectrum. This last additional bin with zero observed events, extends from the end point of the observed spectrum to the maximum energy $E_{\text{max}}$ assumed for the injected spectrum in Eq. 1. This extra bin takes into account the non-observation of events above the highest occupied energy bin in the data HiRes, i.e. at $E > 1.6 \times 10^{20}$ eV for the HiRes spectrum we used [5]. We compute the expected number of events in this last bin using an exposure that we derive from the HiRes data above $10^{20}$ eV, by comparing the published integrated fluxes with the number
of events observed and assuming the exposure is energy independent (above 10^{20} \text{ eV}).

To fit the UHECR data with each predicted spectrum we follow a procedure similar to that of Ref. \cite{21} applied to the bins just mentioned. We reconstruct the measured number of events in each bin from the published data of HiRes (using the error bars \cite{22}) and compare them with the number of events in each bin predicted by each of the models. We choose the value of the parameter $f$ in Eq. \ref{eq:1}, i.e. the amplitude of the injected spectrum, by maximizing the Poisson likelihood function, which is equivalent to minimizing $-2 \ln \lambda$, (i.e. the negative of the log likelihood ratio) \cite{23}. This procedure amounts to choosing the value of $f$ so that the mean total number of events predicted (i.e. the sum of the average predicted number of events in all fitted bins) is equal to the total number of events observed. We then compute using a Monte Carlo technique the goodness of the fit, or $p$-value of the distribution, defined as the mean fraction of hypothetical experiments (observed spectra) with the same fixed total number of events, which would result in a worse, namely lower, Poisson likelihood than the one obtained (in the maximization procedure that fixed $f$). These hypothetical experiments are chosen at random according to a multinomial distribution. We have checked that this procedure when applied to bins with large number of events gives the same results as a Pearson’s $\chi^2$ fit, both for the value of the normalization parameter $f$ and for the goodness of fit. A higher $p$ value corresponds to a better fit, since more hypothetical experimental results would yield a worse fit than the one we obtained. We make one additional requirement on the fit that insures that the predicted flux does not exceed the observed flux at energies below $2 \times 10^{18} \text{ eV}$.

In the next section we present our results the for total UHECR flux, which is dominated by protons at all energies.

3 The proton flux

In this section we find the range of source proton spectrum and distribution parameters $\alpha$, $E_{\text{max}}$, $z_{\text{min}}$ and $m$, consistent with the HiRes observed spectrum \cite{4} at energies $E \geq 2 \text{ EeV}$.

In Fig. 1 and Fig. 2 we show the logarithm of the $p$-value in a color coded scale, from best ($p = 1$) to worse ($p$ close to zero), which measures the consistency level of the predicted UHECR proton flux with the HiRes data, for different parameter ranges.

The high energy part of the predicted spectrum depends mostly on the power law index $\alpha$, the maximum injected proton energy $E_{\text{max}}$ and the minimal
Fig. 1. Consistency level of the predicted UHECR proton flux with HiRes data as function of $E_{\text{max}}$ and $\alpha$ for $m = 0$ and either $z_{\text{min}} = 0$ (in Fig. 1a, left panel), i.e. a continuous distribution of sources, or $z_{\text{min}} = 0.01$ (Fig. 1b, right panel), i.e. with no sources within a 50 Mpc radius. Color coded logarithmic $p$-value scale, from best ($p = 1$) to worse ($p$ close to zero).

Fig. 2. Consistency level of the predicted UHECR proton flux with HiRes data as function of $m$ and $\alpha$ for $E_{\text{max}} = 10^{21}$ eV and either $z_{\text{min}} = 0$ (in Fig. 2a, left panel), i.e. a continuous distribution of sources, or $z_{\text{min}} = 0.01$ (Fig. 2b, right panel), i.e. with no sources within a 50 Mpc radius. Color coded logarithmic $p$-value scale, from best ($p = 1$) to worse ($p$ close to zero).

distance to the sources $z_{\text{min}}$. In Fig. 1 the $p$-values are shown as function of $E_{\text{max}}$ and $\alpha$ for $m = 0$ and either $z_{\text{min}} = 0$ (Fig. 1a, left panel), i.e. a continuous distribution of sources, or $z_{\text{min}} = 0.01$ (Fig. 1b, right panel), i.e. with no sources within a 50 Mpc radius. We can see in the figure that fitting the UHECR data from 2 EeV and above, the initial proton spectrum should be relatively hard, with $\alpha = 2.50 - 2.65$ in Eq.(1). Fig. 1a shows that this range does not depend strongly on $E_{\text{max}}$ for a continuous distribution of sources. If there are no sources within a distance of 50 Mpc distance, thus $z_{\text{min}} = 0.01$, as shown in Fig. 1b, the HiRes observed spectrum is not fitted as well anymore, and a relatively high maximum energy $E = 10^{21}$ eV is required for a reasonable fit, with, say, $p > 0.05$.

The low energy part of the predicted spectrum depends mostly on the power law index $\alpha$ and source evolution index $m$. In Fig. 2 we show the goodness of
Fig. 3. UHECR proton flux fitted to the HiRes data in the energy range $E > 2 \times 10^{18}$ eV of one of the models with best goodness of fit: $m = 0$, $z_{\text{min}} = 0$, $E_{\text{max}} = 10^{21}$ eV and $\alpha = 2.55$.

The fit $p$-value as function of $m$ and $\alpha$ for $E_{\text{max}} = 10^{21}$ eV and again for either $z_{\text{min}} = 0$ (Fig. 2a, left panel) or $z_{\text{min}} = 0.01$ (Fig. 2b, right panel). This figure clearly shows the degeneracy between the parameters $m$ and $\alpha$: as $m$ increases from $-2$ to $3$ the value of $\alpha$ of the best fits decreases from $\simeq 2.6 - 2.7$ to $\simeq 2.4 - 2.5$. Again the fit is worse for $z_{\text{min}} = 0.01$, in which case the $p$-value is never higher than 0.04.

Fig. 3 shows the total predicted UHECR spectrum fitted to the HiRes data in the energy range $E > 2 \times 10^{18}$ eV of one of the models with best goodness of fit, as can be seen in Figs. 1a and 2a. It has $m = 0$, $z_{\text{min}} = 0$, $E_{\text{max}} = 10^{21}$ eV and $\alpha = 2.55$.

4 The GZK photon flux

In this section we discuss the secondary photon fluxes. The main difference between the minimal model we are concentrating on here and other models (see Ref. [9]) is that in the minimal model one fits the UHECR data with extragalactic protons data starting from low energies $E > 2$ EeV, what requires a hard spectrum with index $\alpha > 2.4$ (see Figs. 1a and 2). In this case the GZK photon flux is always sub-dominant, at all energies.

As an example, in Fig. 4 we show the possible range of GZK photon fluxes for the predicted proton spectrum of Fig. 3. The range of photon fluxes is between the upper photon (blue-dotted) line which was calculated with minimal radio
Fig. 4. GZK photon and cosmogenic neutrino spectra (besides the proton spectrum) for the model of Fig. 3 ($m = 0$, $z_{\text{min}} = 0$, $E_{\text{max}} = 10^{21}$ eV and $\alpha = 2.55$). The upper photon line is for minimal radio background and $B_{\text{EGMF}} = 10^{-11}$ G, while the lower photon line for maximal radio background $B_{\text{EGMF}} = 10^{-9}$ G.

background and $B_{\text{EGMF}} = 10^{-11}$ G and the lower photon line corresponding to maximal radio background and $B_{\text{EGMF}} = 10^{-9}$ G. (How the GZK photon flux depends on the radio background and extragalactic magnetic fields assumed can be seen in Ref. [9]).

Here we do not deal with neutrinos in any detail, but just to compare the photon and neutrino fluxes produced in the same GZK processes, in Fig. 4 we also plotted the cosmogenic neutrino flux per flavor for the same model. Even if the neutrino flux is much higher than the photon flux, its detection may be even more difficult due to the strongly reduced probability of neutrinos to produce air-showers.

In Fig. 4 one can see that the best energy range to find GZK photons is $E = 5 - 20$ EeV. At higher energies, the small event statistics will not allow to find a 1% fraction of photons in the UHECR flux, while at lower energies the photon fraction is strongly reduced.

The dependence of the GZK photon fractions on $E_{\text{max}}$, the maximum source proton energy, is shown in Fig. 5. The figure shows the maximum and minimum GZK photon fractions given in percentage of the integrated UHECR fluxes above the energy $E$ for $E = 10^{19}$ eV (left panel) and $E = 10^{20}$ eV (right panel). In order to define the range of possible photon fluxes we use only models with p-values $p > 0.05$ (i.e. we eliminate those models which are inconsistent with the HiRes observed spectrum at the 95 % C.L.). Those shown are the maximum and minimum GZK photon fractions obtained for
Fig. 5. Maximum and minimum GZK photon fractions given in percentage of the integrated fluxes above the energy $E$ as function of $E_{\text{max}}$, the maximum energy of source proton spectra, for $E = 10^{19}$ eV (Fig. 4a, left panel) and $E = 10^{20}$ eV (Fig. 4b, right panel).

Each value of $E_{\text{max}}$ by varying all the other parameters as specified above, and choosing either minimum or maximum intervening backgrounds. The important conclusion coming from this figure is the stability of the GZK photon fractions at $E > 10^{19}$ eV as function of $E_{\text{max}}$. Notice that the expected photon fractions are between $10^{-4}$ and $10^{-3}$ for the whole $E_{\text{max}}$ range we consider (see the left panel). This contrasts with the situation at $E > 10^{20}$ eV (right panel), where the photon fractions depends strongly on $E_{\text{max}}$.

Fig. 6. Maximum and minimum GZK photon fractions given in percentages of the integrated flux above the energy $E$ as function $E$ for maximum source proton energy $E_{\text{max}} = 10^{21}$ eV. Present limits on photon fraction from Auger [24], Yakutsk [25] and combined AGASA/Yakutsk [26] data are also shown.

Finally, in Fig. 6 we show the GZK photon fraction given in percentage of the integrated UHECR flux above the energy $E$ as function of $E$, for the whole parameter space we consider (i.e. maximum source proton en-
ergy $1.6 \times 10^{20} eV \leq E_{\text{max}} \leq 1.28 \times 10^{21} eV$, source evolution parameter $-2 \leq m \leq 3$, power law index $2.3 \leq \alpha \leq 2.9$ and minimum redshift of the sources $0 \leq z_{\text{min}} \leq 0.01$). Present limits on the photon fraction from Auger [24], Yakutsk [25] and combined AGASA/Yakutsk [26] data are also shown in the figure. It is clear that, contrary to the case of top-down models (which are restricted already by present bounds on the GZK-photon fraction [22]), the present limits are well above the expected the GZK photon fraction in the minimal UHECR model by a factor of 10 to 100 depending on the energy (see Fig. 6). The detection of GZK photons in this model will remain as a task for the future.

We have also checked the dependence of the photon fractions in Fig. 6 on the lowest energy for which we fit the HiRes data by changing this energy in the interval $0.3 - 2 \text{ EeV}$. We found no significant changes with respect to Fig. 6 at energies close to $E = 10 \text{ EeV}$, and small changes close to $100 \text{ EeV}$. The highest photon fractions are always at the highest energies, but the best energies to observe photons are close to $10 \text{ EeV}$ due to the larger experimental statistics as well as the smaller dependence of our predictions on the unknown parameters at these energies.

Thus, the expected photon fraction of the integrated flux above $E = 10 \text{ EeV}$ in the minimal UHECR models, is $10^{-4}$ to $10^{-3}$ independently of the unknown parameters we considered. Already Auger South after 5 years of data taking can reach a statistics of $10^4$ events at energies $E > 10 \text{ EeV}$. This would allow, in principle, to detect GZK photons, if they can be discriminated from the large background of proton cosmic rays.

5 Discussion and conclusions

The South site of the Pierre Auger Observatory after several years of data taking will probably be able to reach a photon fraction sensitivity of the order of $10^{-3}$ in the integrated flux close to $E = 10 \text{ EeV}$. As can be seen in Fig. 6 this is the level of the largest GZK photon fraction expected in the minimal UHECR model. Larger future observatories like Auger North plus South [27] and EUSO [28] could probe lower photon fractions if they are able to collect statistics a factor of 5-10 larger than Auger South and have thresholds around $1 - 2 \times 10^{19} eV$ (provided these experiments are sensitive to photon primaries).

We have assumed that the sources emit only protons, however our predictions for GZK photon fractions shown in Fig. 6 would not change too much if nuclei primaries were present too, as assumed in the so called “mixed models” [29]. The reason is that even in mixed models, primary protons dominate the UHECR flux at high energies $E > 50 \text{ EeV}$, i.e. in the energy region where
the primary protons produce secondary GZK photons.

Let us also mention that the photon flux at high energies $E > 10^{18}$ eV could be enhanced by the interaction of UHECR protons with energies $E \sim 1 - 4 \times 10^{19}$ eV with a large infrared background in our galaxy [30] due to the reaction $p + \gamma_{IR} \rightarrow p + \pi^0 \rightarrow p + 2\gamma$. Only $2 \times 10^{-4}$ of the UHECR protons with energy $10-50$ EeV would interact with the infrared background in our galaxy. Thus, the resulting photons, which would have an energy 1-5 EeV, would constitute a small fraction of the order of $4 \times 10^{-6}$ of the integrated UHECR flux at these energies. These are much smaller than the expected GZK photons at energies 1-5 EeV (as shown in Fig. 6).

As a final remark let us mention that even if the GZK photon fluxes considered here are very small, much larger fluxes are possible in more general models, which are not restricted by the condition that all the UHECR spectrum from energies $2 \times 10^{18}$ eV to the largest is explained with extragalactic protons [9].

In conclusion, here we systematically study the possible GZK photon fluxes in the minimal UHECR model in the multi-dimensional parameter space of source proton spectrum power law index $\alpha$ and maximum energy $E_{\text{max}}$, minimal distance to the sources $z_{\text{min}}$ (which is directly connected to the source density), source evolution parameter $m$, average magnetic field value $B$ and extragalactic radio background in the interval $10^{-11} G \leq B \leq 10^{-9} G$. We also consider the dependence of our results on the lowest energy of the HiRes spectrum we chose to fit, varying it in the interval $3 \times 10^{17}$ eV $\leq E_c \leq 2 \times 10^{18}$ eV. In each case we take into account only the models which are consistent with spectrum of cosmic rays observed by HiRes experiment at the 95 % C.L. Our results, presented in Fig. 6, show that future experiments have to reach a sensitivity of $10^{-4} - 10^{-3}$ in the photon to proton fraction for energies $E \geq 10^{19}$ eV in order to detect GZK photons in the minimal UHECR model.

Finally, we want to mention that after this work was finished we got the draft of a paper by G. Sigl in which the GZK photon flux in the minimal UHECR model is also studied. In this paper G. Sigl mainly investigates the effect on the photon fluxes of a three-dimentional magnetic field stucture, and gives only examples of possible photon fluxes in several cases. Here, instead, as mentioned above, we simplify the effect of extragalactic magnetic fields, considering only their average value to be in the interval $10^{-11} G \leq B \leq 10^{-9} G$, while we systematically study the possible photon fluxes in their multi-dimentional parameter space.

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