Ultra-High Energy Photon and Neutrino Fluxes in Realistic Astrophysical Scenarios

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Abstract: UHE-photons and neutrinos are expected to be produced by cosmic rays of $E > 5 \cdot 10^{19}$ eV propagating over intergalactic distances of several 100 Mpc. Although not detected yet, measuring their fluxes would provide a clear signature of the GZK-effect, thereby complementing measurements of the suppression of the CR energy spectrum at the highest energies. This would open up multi-messenger observations that will help to answer open questions about the sources of UHE cosmic rays. To predict photon and neutrino fluxes, simulations of intergalactic propagation of cosmic rays are performed with the publicly available Monte Carlo code CRPropa [1] recently extended to allow also propagation of nuclei [2]. This tool takes into account the interaction of UHE-nucleons, nuclei and photons with the low energy photon background as well as the influence of extragalactic magnetic fields. Different realistic astrophysical scenarios with different source properties and environmental conditions are studied and the results are compared with current experimental upper limits as well as with future sensitivities of experiments.

Keywords: UHE-photons, UHE-neutrinos, CRPropa

1 Introduction

Besides the observation of charged ultra-high energy cosmic rays (UHECR, $E \geq 10^{18}$ eV), additional messenger particles in the same energy region, namely photons (γ) and neutrinos (ν), could help to answer some of the most important questions in astroparticle physics. These particles could be produced at the sources of UHECR or during the propagation of the charged UHECR from their sources to Earth.

The energy spectrum for all particles measured by the Pierre Auger Observatory (Auger) [3, 4] or HIRes [5] indicate a flux-suppression above $\sim 10^{19.5}$ eV. This behavior could be caused by energy losses of the UHECR through interactions with the low energy photon background (e.g. GZK-effect or photodisintegration in case of nuclei), but could also show the limiting acceleration power of the sources. Detecting UHE-photons and -neutrinos which should mostly be produced by the GZK-effect, would favor this scenario. Although not detected yet, the already existing upper limits on the flux of UHE-photons e.g. [6, 7, 8, 9] [1] are able to rule out some exotic cosmic ray source models. The most pressing question, of course, is to find the sources of UHECR. Auger found evidence for anisotropy in the arrival directions of cosmic rays with energies above $5 \cdot 10^{19}$ eV, which exhibit a directional correlation to the position of nearby active galactic nuclei [10]. If detected, UHE-photons and -neutrinos could supply a more accurate estimate of the position of the UHECR sources. Also, the mass composition of cosmic rays in this energy range is not known well, yet. The mentioned anisotropy suggests a lighter composition at the highest energies towards protons, because heavy nuclei would suffer from stronger deflections in magnetic fields. However, measurements of longitudinal development of UHECR induced air showers by Auger indicate a heavier composition above 10 EeV [11].

In this work we perform simulations of the propagation of UHECR with the Monte Carlo code CRPropa version 2.0 (beta) [2], and make predictions for the photon and neutrino fluxes produced during the propagation of charged UHECR. To do so, assumptions about the CR mass composition at the source and about the spatial distribution of sources need to be made. Furthermore, the photon background fields in the infrared and radio regime and the intergalactic magnetic fields are only poorly known, but will influence the propagation of UHECR. For these reasons we assume different astrophysical scenarios where the influence of these different parameters is investigated. Com-

1. As only the photon fraction is presented in [7] the corresponding photon fluxes were calculated from this data using the energy spectrum from [4].

paring the results of this simulation with experimental data will allow us to disfavor some of the astrophysical scenarios.

Production of secondaries UHE-photons and -neutrinos are mainly produced during the propagation of UHECR as decay products from the GZK-effect, which is a resonant pion production on the CMB. For the first resonance $\Delta^+(1232)$ the process is

$$\begin{aligned} p+\gamma \to \Delta^+(1232) &\to p+\pi^0 \\ &\qquad \hookrightarrow \gamma\gamma \\ &\to n+\pi^+ \\ &\qquad \hookrightarrow \mu^+ + \nu_\mu . \end{aligned} \quad (1)$$

For higher energies, further baryonic resonances and higher multiplicities become possible. Below energies of $5 \cdot 10^{19}$ eV also the infrared background significantly reduces the energy loss length for pion production. But here the pair production by protons on the CMB is the dominant process. After the production of photons and electrons these particles themselves interact with the CMB, propagating in an electromagnetic cascade which is driven mainly by pair production and inverse Compton scattering. Also, double- and triple-pair production are considered here. For photon energies above $E \geq 10^{18}$ eV the interaction with the radio background also plays an important role by decreasing the energy loss length. Additionally, the electrons in the cascade emit synchrotron radiation in intergalactic magnetic fields (IGMF). For nuclei, photodisintegration and nuclear decay are considered, too. For pion production the nucleus is treated as a collection of free nucleons, which interact with the photon background as described above and for pair production processes the description given by Blumenthal [12] is followed.

2 Simulations

For simulations presented in this work, we use the 1D-mode of CRPropa, where no deflections in magnetic fields are taken into account, and particles propagate rectilinear. In spite of that, energy losses of the electromagnetic cascades due to synchrotron radiation in IGMF are still considered. For all simulations, continuously distributed sources are assumed. The energy spectra at the sources are modeled to follow a power law with a spectral α and an exponential cutoff at the energy $E_{\max}$:

$$\frac{dN}{dE} \propto E^{-\alpha} \cdot e^{-E/E_{\max}}$$

The combined simulated nucleon- and photon-fluxes are normalized to the number of events counted by the surface detector stations of Auger [4] for energies $E \geq 10^{18.4}\, eV$.

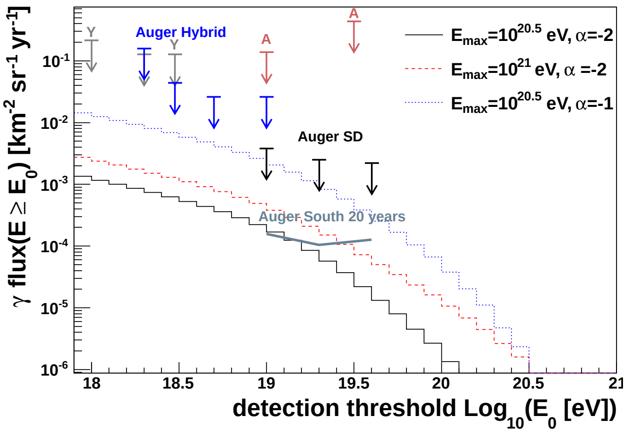

Figure 1: Photon fluxes expected from proton sources in the high-photon scenario for different variations of the source spectra. Additionally, upper limits from [6, 7, 8, 9] and the expected sensitivity of the Auger experiment are shown.

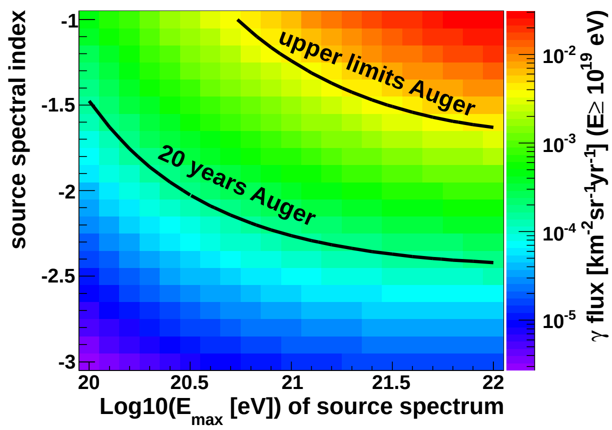

Figure 2: Integrated photon fluxes for $E \geq 10^{19}$ eV expected from proton sources in the high-photon scenario in dependence of the source spectrum parameters α and $E_{\max}$.

2.1 Proton primaries

Photons In this part, the photon fluxes from realistic astrophysical scenarios are estimated. For this purpose the consideration of sources up to a redshift of z=1 is sufficient, as more distant sources do not contribute neither to the nucleon- nor the photon-fluxes. Two astrophysical scenarios are chosen that would result in a *high* and a *low* photon flux:

- **high-photon:** Low radio background from [13], low infrared background from [14], IGMF of 0.01 nG perpendicular to the path of the particles, and source evolution follows the star formation rate [15] $(dN/dz \propto (1+z)^{3.4})$ for $z < 1$).

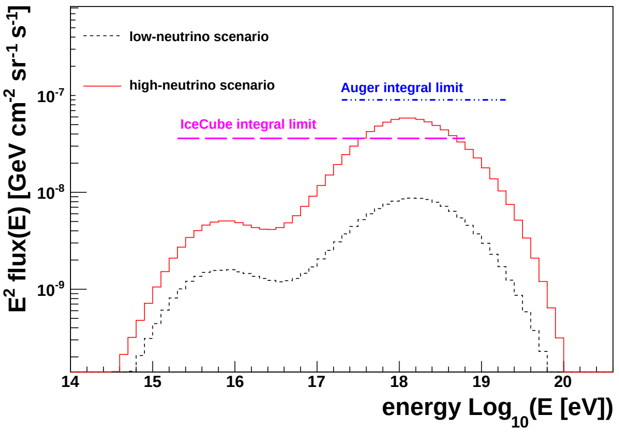

Figure 3: Simulated neutrino fluxes from proton sources. The here used source parameters estimated from the fit with the energy spectrum of Auger [4] are $\alpha = -2.2$ and $E_{\max} = 10^{20.5}$ eV for the high-neutrino scenario and $\alpha = -2.4$ and $E_{\max} = 10^{20.5}$ eV for the low-neutrino scenario. Also included: Integral neutrino limits assuming a E^{-2} spectrum from Auger [19] and IceCube [21] .

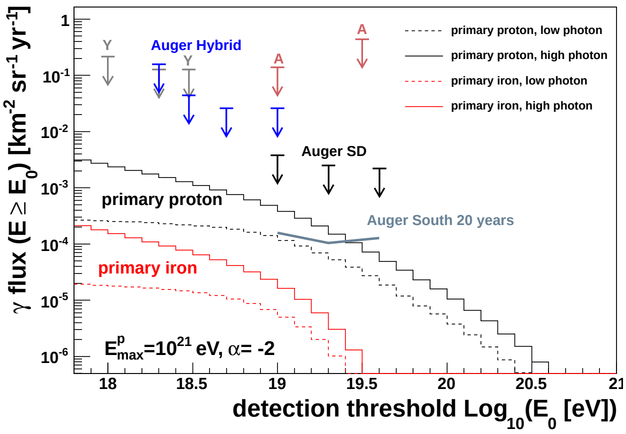

Figure 4: Photon fluxes from a pure proton and pure iron composition at the source, each for the low-photon and the high-photon scenario. The source parameters are $\alpha = -2$ and $E^{\mathrm{p}}_{\max} = 10^{21}$ eV. Additionally upper limits from [6, 7, 8, 9] and expected sensitivity of the Auger experiment are shown.

- **low-photon:** A high radio background [16], a higher infrared background [17], IGMF of 1 nG, and a steeper source evolution as indicated for FRII type galaxies [18].

The resulting spectra of photon fluxes depend strongly on the energy spectrum at the sources, as can be seen in Fig. 1, where the photon flux from the high-photon scenario is shown for different source energy spectra. The strongest experimental upper limits for the photon flux at these energies, as reported by Auger and Yakutsk [6, 7, 9], are marked. The source parameter combinations (α, $E_{\max}$) which are ruled out according to these γ upper limits are shown in Fig. 2. Already now, source spectra with higher maximum energies and flatter spectra are excluded for the here regarded scenarios. Moreover, if UHE-photons are not detected by Auger, the prospective upper limit should restrict the source parameters to more interesting regions.

Similar studies were also performed by [20] regarding only Centaurus A as source of UHECR.

Neutrinos For the prediction of the neutrino flux the maximal distance of the source was extended to z=8. Again, an optimistic and a pessimistic scenario is chosen which differs now only in the source evolution and the infrared background. For the high-neutrino case the sources follow the FRII distribution and the higher infrared background is used. Whereas in the low-neutrino case the sources follow the star formation rate and the low infrared background is assumed. To constrain the source parameters, the experimental energy spectrum from Auger [4] is fitted to the simulated nucleon flux. Only the nucleon data from the simulation is used, as the photon flux is subdominant in the whole fitting region. The parameters for the best fit to the data were $\alpha = -2.2$ and $E_{max} = 10^{20.5}$ eV and $\alpha = -2.4$ and $E_{max} = 10^{20.5}$ eV for the high and low neutrino scenario, respectively. The resulting neutrino fluxes from the high neutrino scenario already crosses the the current integral limits of the IceCube experiment [21] as can see in Fig. 3. Comparison with Kotera *et al.* [22] shows that our simulation agree with them within a factor of two.

2.2 Other primaries

Iron primaries As already mentioned, the chemical composition of cosmic rays at the highest energies is not well known, yet. For this reason we also investigate the impact of other primary particles at the sources of cosmic rays and study the case of pure iron sources for the already introduced low- and high-photon scenarios. In this section $E_{\max}$ is scaled with the atomic number of the nucleus, Z, according to $E_{\max} = Z \cdot E^p_{\max}$, where $E^p_{\max}$ is the maximum energy in the proton case. The resulting photon fluxes for a fixed source spectrum with $\alpha = -2$ and $E^p_{\max} = 10^{21}$ eV are shown in Fig. 4 in comparison to the fluxes from proton primaries. One can see a decrease of the photon flux, as is expected due to the lower energy of the single nucleons in the iron nucleus and the competing interaction photodisintegration. The difference is in the order of one magnitude as also found in [23].

Photon primaries In case of interactions at the source itself, photons are also emitted directly at the sources of UHE cosmic rays. To investigate the effect of those primary photons, we assume a component of 20%, 50% and 90% UHE-photons emitted at otherwise pure proton

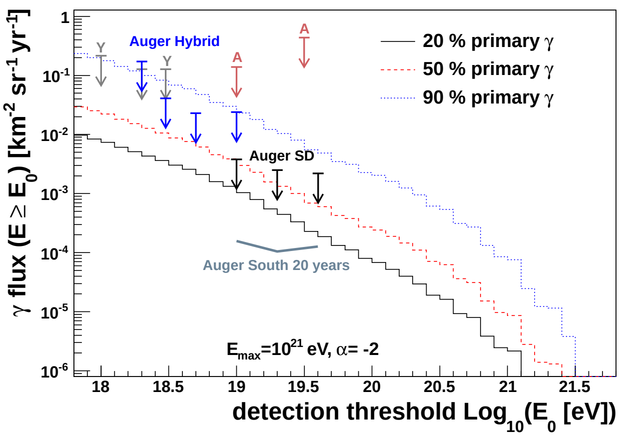

Figure 5: Photon flux from proton sources with a 20%, 50% and 90% fraction of primary photons at the sources for the high-photon scenario and fixed source parameters of $\alpha = -2$ and $E_{\max} = 10^{21}$ eV. Additionally upper limits from [6, 7, 8, 9] and expected sensitivity of the Auger experiment are shown.

sources. Here we use the high-photon scenario and again a fixed source spectrum with $\alpha = -2$ and $E_{\max} = 10^{21}$ eV. The resulting photon fluxes are shown in Fig. 5. A clear increase in the photon flux can be observed in comparison to a pure proton composition at the sources, that would already exceed the experimental upper limits for more than 50 % primary photons at the source.

3 Summary

Simulations of the propagation of cosmic rays are performed for different realistic scenarios where different assumptions on sources and properties of the intergalactic space are made. Comparison of the resulting UHE-photon fluxes for an optimistic photon scenario with experimental upper limit of Auger on the photon flux allows us to put constraints on the source energy spectrum. The yielded predictions for the photon flux decreases in the case of iron primaries and increases in the case of photons produced at proton sources itself. Presently existing limits already allow constraining the photon fraction at the sources to less than 50 % for the paramaters specified. The highest expected neutrino fluxes from the simulations already cross the integral limits of the Icecube experiment and is near to that of Auger at higher neutrino energies. This indicates that future limits could put interesting constraints on the sources of UHECR. Thus, the combination of measured photon and neutrino upper limits or observed fluxes together with measurements of the CR energy spectrum will provide important information about the sources of the highest energy cosmic rays.

Acknowledgement This work has been supported in part by the BMBF under grant 05A08PX1. In Hamburg this work was supported by the DFG through the collaborative research centre SFB 676.

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