Can the extragalactic gamma-ray background be explained by AGN ?

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Abstract. Very high energy gamma-rays from blazars traversing cosmological distances through the meta-galactic radiation field can convert into electron-positron pairs in photon-photon collisions. The converted gamma-rays initiate electromagnetic cascades driven by inverse-Compton scattering with microwave background photons. Using a model for the time-dependent meta-galactic radiation field consistent with currently available far-infrared to optical data, the cascade contributions by faint, unresolved sources like blazars and FRI galaxies have been calculated. We come to the conclusion that depending on what is known so far about AGN, they are not able to produce the total extragalactic flux detected by EGRET. A test for the model will be the upcoming observations with FERMI. It would also be helpful to detect a signal above 100 GeV where the gamma-ray flux declines to 10^{-7}GeV sr^{-1} cm^{-2} s^{-1}.

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INTRODUCTION

The first detection of extragalactic gamma-ray background (EGRB) has been published in [1] who were able to distinguish between a galactic and an extragalactic diffuse component. Since then many authors have make efforts to explain its origin by all kinds of sources and physical processes, including the possibility that the extragalactic background is part of the galactic emission (see recent reviews by [2] and [3]). A long discussed question is if active galactic nuclei (AGN) are able to produce the total detected extragalactic signal. It is a reasonable assumption since blazars, subclass of AGN, are known as powerful gamma-ray emitters. The EGRET detector on board the Compton Gamma-Ray Observatory (CGRO) was able to observe about 70 objects with an average spectral similar to the detected spectral index of the gamma-ray background. Most of he calculations came to the conclusion that between 25% and 90% of the gamma-ray background flux could be due to blazars (e.g. [4], [5], [6]). Only [7] found a 100% contribution adding the effect of flux variability and [8] using a multi-wavelength approach had difficulties not to overproduce the measured flux. [9] discussed another aspect which is a possible contribution by cascade or halo emission. Gamma-rays from extragalactic sources are being absorbed by low energy background photons produced by stars in galaxies. In this photon-photon interaction an electron-positron pair is being produced which is initiating a pair cascade. The result is a secondary photon component at energies about two orders of magnitude below the primary photon energy. A first generation of absorbed TeV photons would therefore convert to GeV emission. If this photons are being absorbed again, inverse Compton scattering would lead to photons in the MeV range. This effect could lead to a second component from each gamma-ray source population to the EGRB. [9] have shown the effect using the model by [7] which accounts already for the whole observed flux. They found depending on the TeV spectrum that the GeV could be as much as an order of magnitude higher including the cascade contribution. The extragalactic magnetic field plays a very crucial role and so [9] emphasized the importance of constraints on the extragalactic magnetic field from such a calculation. Based on this result we found it promising to make a detailed EGRB model for different types of objects, in particular AGN. In the following we summarize the work we have done so far studying the effect of cascading in blazars and Fanaroff-Riley galaxies in the context of the EGRB. For more details see [10] and [11]. .

PAIR CASCADES AND COSMIC GAMMA-RAY SPECTRA

The method of integrating a template spectrum and a luminosity function over redshift is used to calculate the EGRB. At high and very high energies (> 10 GeV) photons can be absorbed by infrared photons via the process of photon-photon pair production. This is an extragalactic process which occurs while the photons are traveling through intergalactic space. Depending on its redshift a non thermal power-law spectrum would show a turn-over at GeV energies. This effect is often described in terms of the cut-off energy E_c which is defined as $\tau_{\gamma\gamma}(E_c) = 1$ whith $\tau_{\gamma\gamma}$ as the optical depth of photon-photon pair production. The produced electrons and positrons undergo inverse Compton scattering with cosmic microwave photons, which leads to a second generation of high energy gamma-ray photons. Is the source located very far away from the earth the photons are absorbed as well and a Compton-pair cascade develops. In the following we use an analytic approximation and only the second generation of photons is being considered. Adding more generations of cascade photons are not changing the result discussed here, because they would contribute at much lower energies ($E < 100$ MeV). The calculation of the absorption requires a detailed knowledge of the metagalactic radiation field (MRF) and its evolution with redshift. In the following the model described in [12] is used with the parameters from the "best-fit" model published in [13]. The cascade flux strongly depends on the redshift and the intrinsic spectral energy distribution of the gamma-ray source (see a detailed discussion in [14]). The absorption and cascade emission of four detected blazars is shown in Fig 1. The redshift of the sources decrease from the top left panel to the panel on the bottom right. The dashed line is the intrinsic spectrum modeled using a broken power-law, the absorption effect is visible as the solid line and the dot-dashed line shows the cascade contribution with no magnetic field present. Note that the upper left panel has an intrinsic power-law spectrum with $\alpha = 1.2$ for $E < 10$ TeV and $\alpha = 2.0$ otherwise while for the other three panels $\alpha = 1.7$ for $E < 0.6$ TeV and $\alpha = 2.5$ otherwise has been assumed. In case of an extragalactic magnetic field the flux would decrease due to the redirection of the charged electron-positron pairs [15], [16]. High magnetic fields would lead to complete isotropization of the cascade flux, which would be visible around the source in a distance of a few Mpc to Gpc as a so called pair-halo [17].

BLAZARS AND FANAROFF-RILEY GALAXIES

The contribution to the gamma-ray background by GeV blazars has been calculated by integrating the EGRET luminosity function over redshift. We used the luminosity function including luminosity and density evolution as derived by [4]. For energies $E > 100$ MeV we used as a singe power-law spectrum with an average spectral index of 1.35. The cascade emission has been calculated as well.

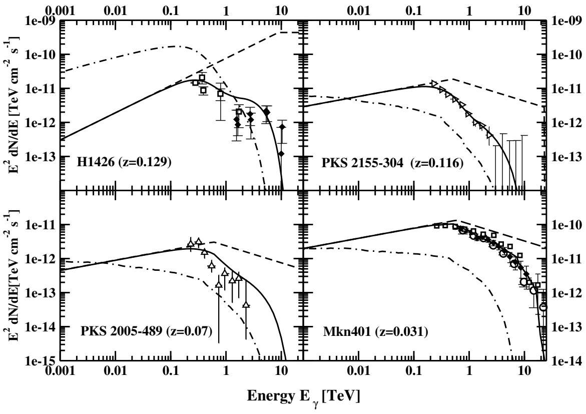

FIGURE 1. TeV spectral energy distribution for four BL Lacs. The data are as in [10]. The intrinsic spectrum is indicated by the dashed line, the absorbed by solid line and the possible cascade emission by the dot-dashed line.

The number of observed TeV blazars is not very large, but many new sources have been detected very recently. But no complete sample is available which could be used to derive a TeV luminosity function. The observed TeV blazars are showing a high X-ray flux and most of the theoretical models predict that the X-ray flux and the gamma-ray flux are connected. Therefore we use an observed X-ray luminosity function of so called X-ray or high peaked blazars [18] with no evolution, to model the TeV blazar population. It was assumed that the energy output in the TeV band is the same as in the X-ray band which is supported by a sample of blazars in e.g. [19]. The spectral energy distribution is described by a broken power-law. Motivated by the most energetic photons observed from TeV blazars 30 TeV is used as an energy upper limit.

The Chandra X-ray observatory detected a number of large scale jets in FRI galaxies. If this emission is of synchrotron origin, kpc-scale jets are sources of high and very high energy emission due to inverse-Compton scattering of galactic photon fields. We fit the X-ray flux of the brightest knots assuming a magnetic field of 300 μG, bulk Lorentz factor of $\Gamma = 3$ and a jet viewing angle of $\Theta = 45$ deg. The result is a typical intrinsic power-law spectrum with $\alpha = 0.75$ for $E < 1$ GeV, a break region between 1 GeV and 100 GeV and a steep power-law for $E > 100$ GeV. The effect of absorption and re-emission has been taken into account, depending on redshift. Together with the radio luminosity function we can estimate the gamma-ray background contribution [11].

The result is shown in Fig.2. The EGRB flux of GeV blazars follows a slightly modified power-law spectrum and a turn-over at about 100 GeV. The effect of the cascade emission is hardly visible, because the photon flux

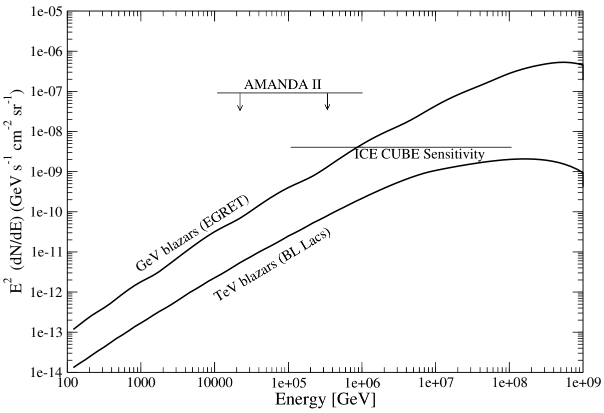

FIGURE 2. Extragalactic neutrino background. The AMANDA limit is taken from [20] and the Ice Cube sensitivity is from [21]. The contribution by AGN are shown as thick solid and dashed lines.

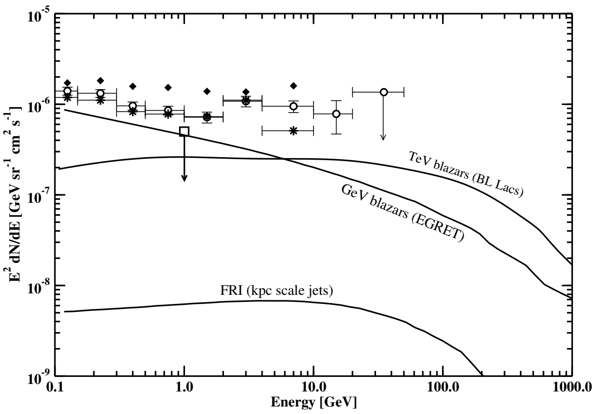

FIGURE 3. Extragalactic gamma-ray background. Data are taken from [23], [24],[25]. The contribution by AGN are shown as thick solid lines.

at TeV energy is very small due to the chosen spectral index. Nevertheless the GeV blazars are able to account for about 60% of the extragalactic gamma-ray background from 100 Mev to 30 GeV. Note that this is more than stated in [4] because we change the average spectral index.

TeV blazars are only able to make a contribution of about 20%. The cascade emission is the main contribution to the GeV EGRB. The spectrum is rather flat in E^2dN/dE and shows a turn-over around 100 GeV.

Gamma-ray emission produced by large scale jets of FRI galaxies would not contribute more than 1% to the extragalactic gamma-ray background.

THE NEUTRINO SKY

The calculation of the neutrino flux is a good method to test some models for the gamma-ray background since the limits and sensitivities of existing and upcoming neutrino detectors have been greatly improved recently. If the gamma-ray emission is due to neutral pion production in relativistic jets one can obtain the neutrino emission by pion production. This is possible for GeV and TeV blazars, but not for FRI galaxies, since the gamma-ray emission is assumed to be of leptonic origin. A very simple approximation for the neutrino spectrum of a blazar is used based on detailed Monte Carlo results by [22]. A broken power-law spectrum has been assumed with an exponential cut-off for both blazar populations $E^2dN/dE \propto E^{-\alpha_\nu}$ with $\alpha_\nu = 1.25$ for $E < 10^7$ GeV and $\alpha_\nu = 0.5$ for $E > 10^7$ GeV. As discussed in [22] a high energy cut-off of 10^9 GeV has been chosen which is due $\mu^\pm$ synchrotron losses. The luminosity function and evolution has been treated as in the gamma-ray background calculation. The result is shown in Fig.2. The neutrino flux is well below the limit set by AMANDA but a population of hadronic blazars as used in the model could be detectable with Ice Cube.

CONCLUSIONS

Here the possibility was discussed if absorption and re-emission in pair-cascades can be responsible for the "missing flux". We conclude that based on what we know about the different populations of AGN producing high and very high energy photons, they are only able to account for about 80% of the observed GeV EGRB. The main contribution of about 60% can be produced in GeV blazars showing a distinct peak in the studied energy region. Only about 20% of the flux could be explained by TeV blazars. The inferred neutrino emission is still in agreement with recent neutrino limits.

Interestingly both blazar contribution show a turn-over in the flux between 100 and 1000 GeV. This means that the main flux contribution comes from sources amount $z \leq 1$ where the cut-off energies is about 100 GeV. To test the predictions of this model it would be interesting to look for an extragalactic background signal above 100 GeV, which should be around 10^{-7}GeV sr^{-1} cm^{-2} s^{-1}. A hypothetical EGRB above TeV energies should have a flux which is more than two orders of magnitude below the EGRET data.

Studying a pair halo of a single source it is known that the cascade flux is very sensitive to the maximum energy and slope of the blazar spectrum changing the luminosity in the GeV energy band significantly. In our model the total luminosity of a blazar is fixed by the luminosity function. It is crucial to define if the cascade flux is part of the total luminosity or not. If the relation between X-ray (or radio) and gamma-ray luminosity function is based on theoretical blazar models, the cascade flux adds to the direct spectrum. An extention of the intrinsic gamma-ray flux to higher energies and flatter spectra would then lead to a large increase of the cascading photons [9]. If the gamma-ray luminosity function is obtain using blazar observations the cascade flux would already be included if the extragalactic magnetic field is very small. A higher cascade flux would not change the result dramatically since the total luminosity will stay the same. So the largest uncertainty in our model is the luminosity function for TeV blazars which is not known yet. As a check for the assumed luminosity function we have calculated the number of blazars which would be observable with Imaging Air Cherenkov Telescopes (IACT). We have included the effect of extragalactic absorption, parameters of the telescopes and of the observational technique in general. We found reasonable numbers of ten blazars for Whipple-like telescopes located mostly at redshifts around 0.05 and roughly a few hundred for recent IACTs with an average redshift of 0.1 [10].

As already mentioned the extragalactic magnetic field has a large impact on the cascade flux. We have assumed that the magnetic field in the voids outside the large scale structure where most of the pair production takes place is very low $> 10^{-20}$ Gauss. Then the cascade emission would be observable at the location of the gamma-ray source and so it would be part of the detected flux. For a higher magnetic field the electron-positron pairs are redirected around the source building up to an isotropic pair-halo. But an isotropized distribution of electron (and positrons) would produced unbeamed gamma-ray photons which would lead to a lower flux of about a factor of 100. But in this case and under the assumption that FR galaxies and BL Lacs are the same type of object viewed from different angles, we would expect the FR galaxies which are about a factor of 100 more numerous than BL Lacs to account for the missing flux with their isotropized pair-halos.

The successful launch of the gamma-ray satellite FERMI which has an enhanced sensitivity compared with EGRET the origin of the EGRB might be able to solve the question. If FERMI is able to resolve the gamma-ray background by point source detection the result can be used to draw conclusion on the distribution and evolution of AGN. If FERMI still detects an extragalactic residue the search for the origin of the EGRB will pose a new challenge to gamma-ray astronomy.

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