BL Lac Contribution to the Extragalactic Gamma-Ray Background

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Abstract. Very high energy gamma-rays ($E_\gamma > 20$ GeV) from blazars traversing cosmological distances through the metagalactic radiation field can convert to electron-positron pairs in photon-photon collisions. The converted gamma rays initiate electromagnetic cascades driven by inverse-Compton scattering off the microwave background photons. The cascades shift the injected gamma ray spectrum to MeV-GeV energies. Randomly oriented magnetic fields rapidly isotropize the secondary electron-positron beams resulting from the beamed blazar gamma ray emission, leading to faint gamma-ray halos. Using a model for the time-dependent metagalactic radiation field consistent with all currently available far-infrared-to-optical data, we compute (i) the expected gamma-ray attenuation in blazar spectra, and (ii) the cascade contribution from faint, unresolved blazar to the extragalactic gamma-ray background as measured by EGRET, assuming a generic emitted spectrum extending to an energy of 10 TeV. The latter cascade contribution to the EGRET background is fed by the assumed >20 GeV emission from the hitherto undiscovered sources, and we estimate their $dN$-$dz$ distribution taking into account that the nearby ($z<0.2$) fraction of these sources must be consistent with the known (low) numbers of sources above 300 GeV.

INTRODUCTION

An isotropic, diffuse background radiation presumably due to faint, unresolved extragalactic sources has been observed in nearly all energy bands. The confirmation of an extragalactic gamma-ray background by EGRET (Energetic Gamma-Ray Experiment Telescope) on board the Compton Gamma Ray Observatory has extended the spectrum up to an energy of $\sim 50$ GeV. A first analysis of the data resulted in a total flux of $(1.45 \pm 0.05) \cdot 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ above 100 MeV and a spectrum which could be fitted by a power law with an spectra index of $-2.1 \pm 0.03$ [1]. These values are strongly dependent on the foreground emission model which is subtracted from the observed intensity to obtain the extragalactic residual [2]. Since using the old foreground model, a residual GeV halo remained after subtraction (in addition to the isotropic extragalactic background), the foreground model had to be improved. This lead to a new analysis of the EGRET data, and a new result for the extragalactic background spectrum, now showing a dip at GeV energies and an overall weaker intensity of $(1.14 \pm 0.12) \cdot 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ [3]. This new result can help us to understand the origin of the extragalactic background radiation.

Since EGRET detected a large number of extragalactic gamma-ray sources belonging to the blazar class of AGN, a reasonable assumption is that the gamma background is produced by unresolved AGN. Using a gamma-ray luminosity function from EGRET data [4] Chiang & Mukherjee (1998) came to the result that only 25% to 50% of the
gamma background could be explained by blazars. [5] were able to explain 100% of the background, but were facing a problem with the deficit of observed faint, nearby blazars. The new idea which will be presented in this paper is to extend the existing models by assuming a population of BL Lacs with a spectral energy distribution such that their flux at EGRET energies is too low to be generally detected, while their very high energy gamma ray flux is strong. Since most of these sources are at redshifts high enough for pair attenuation to take place, a significant part of their VHE emission is reprocessed by cascades contributing to the diffuse background, but not to the single source counts.

During the paper we use a Hubble constant of $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a flat universe with the cosmological parameters $\Omega = 0.3$ and $\Omega_\Lambda = 0.7$.

**GAMMA-RAY BACKGROUND**

If the gamma-ray background is produced by unresolved sources, it can be described by

$$F_{E\gamma} = \frac{1}{\Omega} \int_0^{z_m} \frac{dV}{dz} \int_{L_{\min}}^\infty \frac{dN}{dVdL} F_{E\gamma}(z,L) dL,$$

with $\Omega$ the solid angle coverage of the survey ($\Omega_{\text{EGRET}} = 10.4$), $dV/dz$ the volume element, $L_{\min}$ is the luminosity of the weakest source, $dN/dVdL$ the luminosity function and $F_{E\gamma}(z,L)$ the flux of the gamma sources, depending on their luminosity and redshift. The luminosity function of resolved EGRET sources, extended to the faint end has been computed by [4]. We used their model changing only the spectral index from $\alpha = 2.1$ to $\alpha = 2.3$. The new spectral index was determined by fitting the reanalyzed EGRET data at $< 2.0 \text{ GeV}$.

The remaining excess of the measured gamma-ray background we ascribe to high-energy peaked blazars belonging to the HBL and ExBL classes (defined by [6]). We
FIGURE 2. Spectrum of the extragalactic gamma-ray background (open circles: Sreekumar (1998), filled diamonds: Strong et al. (2004)). The contribution of the HBL component (thick solid line) is compared with the spectrum without any absorption and reemission (thin solid line) and the contribution of the secondary photons only (dashed line).

calculate the flux from this sources using equation 1. The spectral energy distribution of these sources between 100 MeV and 10 TeV and their luminosity function (LF) is poorly known, and we have to make some theoretical assumptions for them which are described the next sections.

**TEMPLATE SPECTRA**

A number of extragalactic gamma-ray sources have been detected with imaging air-Cherenkov telescopes (Table 6, [7]). Four of them (with redshifts \(z = 0.03, 0.03, 0.129, 0.048\)) were bright enough to resolve their spectra in the TeV energy band. The observed spectra are presumably modified by gamma ray attenuation, i.e.

\[
F_{\text{obs}}(E) = F_{\text{int}}(E) \exp[-\tau_{\gamma\gamma}(E, z)]
\]

where \(\tau_{\gamma\gamma}(E, z)\) is the optical depth for gamma-rays (Fig. 1). We used various model parameters for the metagalactic radiation field (MRF) to bracket the range of the unabsorbed (intrinsic) spectra.

Depending on the model of the MRF the intrinsic spectra show turnovers or broad maxima around a few TeV. The intrinsic spectrum of H1426+428 which has a larger redshift \((z=0.129)\) could have a maximum at 10 TeV or higher. We use a mean of the spectra of Mkn501, Mkn421 and ES1959+650 as a template for the HBL-type sources and a spectrum like H1426+428 as the template spectrum for the ExBL-types. Each template spectrum is modeled using two power laws. The parameters are two spectral indices and the location of the maximum. For HBL the spectral index at low energies is
FIGURE 3. Spectrum of the extragalactic gamma-ray background. The contribution of the ExBL component (thick solid line) is compared with the spectrum without any absorption and reemission (thin solid line) and the contribution of the secondary photons only (dashed line).

\[ \alpha = 1.7 \text{ and at high energies } \alpha = 2.3 \text{ with a maximum at 4 TeV. The spectral index of the ExBLs is } \alpha = 1.2 \text{ with a maximum at 10 TeV.} \]

The absorption of the primary photons is calculated using the MRF model presented in [8], and the reemission is calculated using the radiative transfer equation employing an inverse-Compton emission term due to scattering off the microwave background. The flux from a population of gamma-ray sources contributing to the gamma-ray background is the sum of the primary and the secondary flux \[ F_E(\gamma(z_q, L)) = F_{E_p}(\gamma(z_q, L)) + F_{E_s}(\gamma(z_q, L)). \]

**TEV-LUMINOSITY FUNCTION**

Although the secondary cascade contribution is likely to be isotropic, and therefore much fainter than the beamed primary gamma rays, we ignore this effect which is compensated by the correspondingly larger number of hosts which contribute to the extragalactic background light. By doing so, we must use the LF of the parent population of the secondary emission, e.g. the LF of XBLs and ExBLs. HBL and ExBL are x-ray selected BL Lacs showing indications of correlated x-ray/gamma ray emission. We will use x-ray observations to develop a TeV-luminosity function. Using the ROSAT-All-Sky-Survey, [9] and [10] could develop a luminosity function with a maximum in the number of sources at \( z=0.2 \). [11] and [12] found a maximum of sources around \( z=0.3 \) using a sample of the Einstein-Medium-Sensitivity Survey and the Radio-Emitting-X-Ray-Sources catalog, respectively. We will instead use the results of [13] who combined all the available data. To obtain a relation between the gamma-ray flux and x-ray flux we used the calculations from [14]. They presented for 33 BL Lacs multi-wavelength spectra using a theoretical SSC-model and various observations. From their results we fitted a relation between the luminosity at 1 keV \( L(1 \text{ keV}) \) and the gamma-ray luminosity.
FIGURE 4. Spectrum of the extragalactic gamma-ray background. The total spectrum is produced by three components: EGRET sources with a spectral index of 1.3 (thin solid line), HBL (dotted-dashed line) and ExBL (dashed line). For all three component the effect of extragalactic absorption and reemission via inverse Compton scattering is taken into account.

above 0.3 TeV $L_{\text{TeV}}$

$$L_{\text{TeV}} = 2.6535 \cdot 10^{-4} L_{(1 \text{ keV})}^{0.15781} \ [10^{48} \text{ erg s}^{-1}]. \quad (3)$$

The TeV-luminosity function can be written as broken power law $\frac{dN}{dV} (dL_{\text{TeV}}) \propto (L_{0,\text{TeV}})^{\alpha_{\text{LF}}}$ with $\alpha_{\text{LF}} = -0.9$ for $L_{0,\text{TeV}} \leq L_{B}$ and $\alpha_{\text{LF}} = -1.4$ for $L_{0,\text{TeV}} > L_{B}$ with $L_{B}$ break luminosity. The evolution can be described by

$$\rho(z) \propto (1 + z)^{\alpha_{\rho}}. \quad (4)$$

with a steep rise of $\alpha_{\rho} = 10$ for $z \leq 0.15$ and $\alpha_{\rho} = -3$ for $z > 0.15$ (values fitted from the distribution shown in Beckmann et al. 2003).

The maximum and the minimum of the luminosity function has been calculated from the maximum and minimum of the x-ray LF. The absolute value of the luminosity function has been chosen to match the EGRET gamma-ray background data. The bright $(L_{\text{TeV}} > 2.7 \cdot 10^{-4} \ [10^{48} \text{ erg s}^{-1}])$ sources are defined as ExBLs while the faint end of the LF is assumed to represent the HBLs. The number density is comparable with the observed EGRET blazar number density.

DISCUSSION

The results for the various contributions to the extragalactic gamma-ray background are shown in Figure 4. The thin solid line denotes the EGRET blazar contribution. Due to the new spectral index and the reanalyzed EGRET data the unresolved EGRET blazars now produce about 75-80% of the background flux. The dashed line represents the
background flux made due to the HBL population, while the dot-dashed line describes
the flux corresponding to the ExBL contribution. Comparing the total flux as a sum of
the three contributions and the EGRET data, the agreement is acceptable. As can be
seen in Fig. 2 and Fig. 3 the primary flux of the BL Lac population produces only a
small contribution in the EGRET energy range. The secondary photons can contribute
about 20% to the gamma-ray background. Although the number of ExBL is less then
10% of the total number of BL Lac objects the flux is of the same order of magnitude
as the HBL flux. The adopted values of the spectral index and the maximum at 10 TeV
have a large influence on the secondary photon contribution.

The number density of BL Lacs in our model is comparable with that of the EGRET
blazars. Nevertheless, only 7 HBLs have been observed with Imaging Air Cherenkov
Telescopes above 300 GeV (in the published records). The reason for this comparatively
small number is the effect of pair attenuation and the limited sensitivity of the Cherenkov
telescopes. E.g., for AGN at a redshift of 0.2 photons with energies > 300 GeV are
undergoing the pair production process. With Cherenkov Telescopes of the Whipple
type ($E_{\text{thr}} \approx 300, F_{\text{lim}} \approx 10^{-11}$) still most sources within this redshift range are too faint
to be detected in a typical 10-50 h observation campaign. The observational constraint
of small zenith angles further reduces the number of observable sources number by a
factor of roughly $\sim 1/4$. Assuming the number density to fit the gamma-ray background
data a telescope of the Whipple type would only be able to observe $\sim 18$ BL Lacs from
this population.

Our assumptions can be tested by the next generation of Cherenkov Telescopes. Fig. 5
shows the number of BL Lacs depending on the flux limit and the threshold energy of a
telescope. A telescope with a threshold energy of 50 GeV and a flux limit of $F_{\text{lim}} \approx 10^{-11}$
should in principle be able to observe about 25% of 1500 sources.
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REFERENCES

1. Sreekumar, P. et al. 1998, ApJ, 494 523
2. Hunter, S. D. et al. 1997, ApJ, 481, 205
3. Strong, A.W., Moskalenko I.V. & O. Reimer, O. 2004, acc. bei A&A, astro-ph/0405441
4. Chiang, J. und Mukherjee, R. 1998, ApJ, 496, 752
5. Stecker, F. W. und Salamon, M.H. 1996, ApJ, 464, 600
6. Ghisellini, G. et al. 1998, MNRAS, 301, 451
7. Horan, D. et al. 2002, ApJ, 571, 753
8. Kneiske, T.M., Mannheim, K. & Hartmann, D. 2002, ApJ, 386, 1
9. Bade, N. et al. 1998, A&A, 334, 459
10. Laurent-M"uhleisen, S.A. et al. 1999, ApJ, 525, 127
11. Rector, T.A. et al. 2000, AJ, 120, 1626
12. Caccianiga, A. 2002, ApJ, 566, 181
13. Beckmann, V., Engels, D., Bade, N. und Wucknitz, O. 2003, A&A, 401, 927
14. Costamante, L. und Ghisellini, G. 2002, A&A, 384, 56
15. Kneiske, T.M., Bretz, T., Mannheim, K. & Hartmann, D. 2004, ApJ, 413, 807