Contribution from blazar cascade emission to the extragalactic gamma-ray background: what role does the extragalactic magnetic field play?

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Accepted 2012 February 14. Received 2012 February 11; in original form 2011 December 21

ABSTRACT

We estimate the contribution to the extragalactic gamma-ray background (EGRB) from both intrinsic and cascade emissions produced by blazars, using a simple semi-analysis method for two models of the blazar gamma-ray luminosity function (GLF). For the cascade emission, we consider two possible contributions: in case I, the flux of the cascade emission is lower than the Fermi Large Area Telescope (LAT) sensitivity, which is independent of the extragalactic magnetic field (EGMF); in case II, the flux of the cascade emission is larger than the Fermi LAT sensitivity, but the emission angle is larger than the LAT point-spread-function angle, which depends on the EGMF. Our results indicate the following. (i) The blazar contribution to the EGRB is dominant, although it depends on the GLF model and the EGMF. (ii) The EGMF plays an important role in estimating the contribution from the cascade emission produced by blazars, so the contribution from the cascade emission will significantly alter the EGRB spectrum when the strength of the EGMF is large enough (i.e. $B_{\text{EGMF}} > 10^{-12}$ G). (iii) Because the cascade emission in case II reaches saturation when the strength of the EGMF is $\sim 10^{-11}$ G, it is very possible that the contribution from the cascade emission produced by blazars can be considered as another method to probe the upper limit of the strength of the EGMF.

Key words: magnetic fields – galaxies: active – galaxies: luminosity function – gamma-rays: diffuse background.

1 INTRODUCTION

The gamma-ray sky observed by the Large Area Telescope (LAT) onboard the Fermi Gamma-Ray Space Telescope consists of resolved gamma-ray emitters, such as normal galaxies, active galactic nuclei (AGNs), gamma-ray bursts (GRBs) and pulsars, etc., and diffuse gamma-ray radiation including emission from the Galaxy and the extragalactic gamma-ray background (EGRB; e.g. Abdo et al. 2010a,b). Not much is known about the origin of the EGRB, and it is one of the fundamental unsolved problems in astrophysics. The EGRB was first detected by the SAS-2 satellite (Fichtel et al. 1975). Later, in the 1990s, the Energetic Gamma-Ray Experiment Telescope (EGRET) onboard the Compton Observatory measured its spectrum at 0.03–50 GeV with good accuracy (Sreekumar et al. 1998; Strong, Moskalenko & Reimer 2004). Recently, the LAT has made a new measurement of the EGRB spectrum (Abdo et al. 2010b). This has been found to be consistent with a featureless power law of photon index of $\sim 2.41$ in the 0.2–100 GeV energy range. The observed integrated flux above 100 MeV is $(1.03 \pm 0.17) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, which is lower than $(1.43 \pm 0.05) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ observed by EGRET (Strong et al. 2004; Abdo et al. 2010b).

Various types of unresolved gamma-ray sources have been proposed as the possible contributors to the EGRB, such as AGNs (e.g. Padovani et al. 1993; Chiang & Mukherjee 1998; Giommi et al. 2006; Narumoto & Totani 2006; Dermer 2007; Cao & Bai 2008; Inoue & Totani 2009; Venters, Pavlidou & Reyes 2009; Venters 2010; Inoue 2011; Ajello et al. 2011), star-forming galaxies (e.g. Pavlidou & Fields 2002; Fields, Pavlidou & Prodanovic 2010; Makiya, Totani & Kobayashi 2011) and starburst galaxies (e.g. Thompson, Quataert & Waxman 2007; Makiya, Totani & Kobayashi 2011). Because blazars are the dominant extragalactic gamma-ray sources, it is natural to expect the intrinsic emission of an unresolved population of blazars to account for a sizable contribution to the EGRB. However, because of the uncertainties of the gamma-ray luminosity function (GLF) and the spectrum index distribution (SID) of blazars, this contribution to the EGRB is under discussion. Stecker & Venters (2011) and Inoue & Totani (2009) have suggested that this contribution is dominated by the emission from unresolved blazars, while Ajello et al. (2011) and Abdo et al. (2010) have argued that unresolved blazars produce a small fraction of the EGRB.

Additionally, very high energy (VHE) photons from blazars will interact with the ultraviolet–infrared photons of extragalactic...
2 CONTRIBUTION TO THE EGRB FROM BLAZARS

2.1 Blazar gamma-ray luminosity function

To estimate the contribution to the EGRB from unresolved blazars, the blazar GLF is required. However, because of the small size of the sample, it is difficult to build a GLF directly using the current gamma-ray-loud blazar sample. However, the luminosity functions (LFs) of blazars at other wavelengths (e.g. radio or X-ray) have previously been widely studied (e.g. Dunlop & Peacock 1990; Hasinger, Miyaji & Schmidt 2005). Moreover, it is believed that the gamma-ray emission of blazars will correlate with the emissions at lower energy bands. For instance, a good correlation has been found between the gamma-ray luminosity and radio luminosity (e.g. Ackermann et al. 2011; Ghisellini et al. 2011). Also, Ghisellini et al. (2010) have found a positive correlation between the jet power and the luminosity of the accretion disc in some blazars. Hence, the GLF is required. However, because of the small size of the blazar GLF constructed by Narumoto & Totani (2006): the pure luminosity evolution (PLE) and luminosity-dependent density evolution (LDDE) models. Narumoto & Totani (2006) limited the model parameters by using a likelihood analysis of the observed redshift and gamma-ray flux distributions of the EGRET blazars. It was found that the LDDE model gives a better fit to the observed distributions than the PLE model. For the blazar GLF \( \rho_L(L, z) \) and its parameters in each model, we use those given by Narumoto & Totani (2006).

2.2 Intensity of the EGRB from the intrinsic emission of blazars

In order to estimate the EGRB intensity from the intrinsic emission of blazars, we need the SID of the Fermi-LAT resolved blazars. In the clean sample of the First LAT AGN Catalogue (ILAC), corresponding to 11 months of data collected in science operation mode, there are 523 blazars (Abdo et al. 2010a). Their energy spectra between 0.1 and 100 GeV can be fitted with a power-law spectrum with photon index \( \Gamma \). The photon-index distribution is compatible with a Gaussian distribution. However, as argued by Abdo et al. (2010a), sources with high spectral indices are more easily detected by the LAT, and therefore the observed photon-index distribution tends to be harder than the intrinsic one. As shown in Abdo et al. (2010a) (see their fig. 1), when the integrated flux \( F_{\gamma, >100} \) above 100 MeV is larger than \( 7 \times 10^{-8} \) photons cm\(^{-2}\) s\(^{-1}\), the LAT detected all sources irrespective of their photon indices, fluxes or positions in the specific sky. For sources with \( F_{\gamma, >100} \geq 7 \times 10^{-8} \) photons cm\(^{-2}\) s\(^{-1}\), the spectral photon-index distribution, which is the intrinsic SID, is also compatible with a Gaussian distribution. This is given by (Abdo et al. 2010a)

\[
\frac{dN}{d\Gamma} = \exp\left[\frac{-{\Gamma - \mu}^2}{2\sigma^2}\right],
\]

with a mean of \( \mu = 2.40 \pm 0.02 \) and a dispersion of \( \sigma = 0.24 \pm 0.02 \).

When the GLF and the intrinsic SID are given, the EGRB intensity \( F_{\text{EGRB}}(E) \) (in units of photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) MeV\(^{-1}\)) from the intrinsic emission of blazars is given by

\[
F_{\text{EGRB}}(E) = \eta \int_{\Gamma_{\text{min}}}^{\Gamma_{\text{max}}} \frac{dN}{d\Gamma} \int_0^{\Gamma_{\text{max}}} d\Gamma_{\text{min}} \int_0^{\Gamma_{\text{max}}} d\Gamma_{\text{max}} dL_\gamma \rho_L F_\gamma(E, z, \Gamma) \times e^{-\tau(z, E)} \left[1 - \alpha F_{\gamma, >100}\right],
\]

Here, \( \Gamma_{\text{min}} = 1.2 \) and \( \Gamma_{\text{max}} = 3.0 \) are the minimum and maximum values of the photon index, \( z_{\text{max}} = 5.0 \) is the maximum redshift and \( L_{\gamma, \text{min}} = 10^{47} \) erg s\(^{-1}\) and \( L_{\gamma, \text{max}} = 10^{49} \) erg s\(^{-1}\) are the minimum and maximum luminosities, respectively. Also, \( F_\gamma(E, z, \Gamma) \) is the intrinsic photon flux at energy \( E \) of a blazar with gamma-ray luminosity \( L_\gamma \) and a power-law spectrum at redshift \( z \), and it is given by (Venters et al. 2009)

\[
F_\gamma(E, z, L_\gamma, \Gamma) = \frac{L_\gamma}{4\pi d_L^2(z)E_\gamma^\Gamma (1+z)^{2-\Gamma}} \left(\frac{E}{100\text{ MeV}}\right)^{-\Gamma}.
\]

Here, \( E_\gamma^\Gamma = (100\text{ MeV}) \times (1.6 \times 10^{-4}) \) erg and \( \tau(z, E) \) is the optical depth of the EBL for the sources at redshift \( z \) emitting gamma-ray photon energy \( E \). We use the model of Finke, Razzauque & Dermer (2010) to derive \( \tau(z, E) \), Fig. 1 presents the optical depths expected in this EBL model as a function of the photon energy \( E \) for sources at different redshifts. Here, \( \alpha F_{\gamma, >100} \) is the detection efficiency.
The optical depths expected in the EBL model of Finke et al. (2010) as a function of the photon energy \( E \) for sources located at \( z = 0.02, 0.2, 0.5, 1.0, 1.5, 2.0, 3.0 \) and 4.5, from bottom to top.

The LAT at the photon flux \( F_{\gamma, \gamma > 100} \), which corresponds to the integrated flux above 100 MeV from the sources at redshift \( z \) with \( L_\gamma \) and \( \Gamma \), and \( F_{\gamma, \gamma > 100} = L_\gamma / (100 \text{ MeV} \times z \times L_{\gamma, \Gamma}) \times 10^{-11} \text{ MeV} \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \), is the normalization factor and \( \lambda = (7) \).\( \dfrac{d\eta}{d\Gamma} \) is the rest mass of electrons, \( \gamma_{\text{obs}} = 10\gamma_{\text{obs}}/\Gamma \) is the EGMF of strength and \( \eta \) in units of \( \dfrac{L_\gamma}{\Gamma} \). The redirected secondary gamma-ray photons arrives at a point by synchrotron emission are negligible because the ratio between secondary-generation electrons is negligible at the GeV range (Kneiske & Mannheim 2008). The energy losses of the electrons by synchrotron emission are negligible because the ratio between the cooling times of inverse Compton scattering CMB photons and synchrotron emission is very small, \( \sim 10^{-6} \), even when the upper limit of the EGMF \( \sim 10^{-9} \text{ G} \) is used.

For the cascade emission of blazars, we follow the geometry of the cascade process given by Dermer et al. (2011). In this geometry, the VHE photons emitted at an angle \( \theta_1 \) by a blazar at distance \( d \) can convert into electron–positron pairs via photon–photon absorption with the photons of the EBL, after travelling a mean distance \( \lambda_{\gamma\gamma} = \frac{d(\text{obs})}{\text{E}\text{.VHE}} \), where the cascade spectrum is a power-law spectrum with photon index 1.5 (Dermer et al. 2011; Huan et al. 2011).

\[ F_{\gamma, \gamma > 100}^\text{cascade}(E, z, L_{\gamma, \Gamma}) = \frac{81\pi}{16\lambda_{\gamma\gamma}^3} \frac{m_e c^2}{U_{\text{CMB}}} \int_0^{\infty} \frac{d\gamma}{\gamma^8 \exp[3\epsilon_{\gamma}/4\gamma^2 \epsilon_{\text{CMB}}(1 + z)] - 1} \int_{2\gamma}^{\gamma_{\text{max}}} \frac{d\gamma'}{\gamma'} \int_{L_{\gamma, \Gamma}}^{L_{\gamma, \text{max}}} \frac{dL_{\gamma'}}{L_{\gamma, \Gamma}} \rho_{\gamma} \omega(F_{\gamma, \gamma > 100}). \]

Here, the dimensionless energy \( \epsilon_{\gamma} = E \times 10^8/(5.11 \times 10^5) \), \( \epsilon_{\text{CMB}} = 1.24 \times 10^{-9} \) in units of \( m_e c^2 \), is the average CMB photon energy at \( z = 0.0 \) and \( \lambda_{\gamma\gamma} = 2.426 \times 10^{-10} \text{ cm} \) is the Compton length. For the maximum dimensionless energy of intrinsic TeV photons \( \epsilon_{\gamma, \max} \), we take \( \epsilon_{\gamma, \max} = 2.0 \times 10^3 \), corresponding to \( E_{\gamma, \text{VHE}} = 100 \text{ TeV} \). The emission from the secondary-generation electrons or more than secondary-generation electrons is negligible at the GeV range (Kneiske & Mannheim 2008). The energy losses of the electrons by synchrotron emission are negligible because the ratio between the cooling times of inverse Compton scattering CMB photons and synchrotron emission is very small, \( \sim 10^{-6} \), even when the upper limit of the EGMF \( \sim 10^{-9} \text{ G} \) is used.

The EGRB intensity in case I, independent of the EGMF, is given by

\[ F_{\gamma, \gamma > 100}^\text{i EGRB}(E) = \eta \int_{\gamma_{\min}}^{\gamma_{\max}} \frac{dN}{d\Gamma} \int_0^{\epsilon_{\gamma, \max}} \frac{d\epsilon}{\epsilon} \frac{d^2V}{dz d\Omega} \times \int_{L_{\gamma, \min}}^{L_{\gamma, \max}} dL_{\gamma} \rho_{\gamma} F_{\gamma, \gamma > 100} \times e^{-\tau(E, z)} \left[ 1 - \omega(F_{\gamma, \gamma > 100}) \right], \]

where \( F_{\gamma, \gamma > 100} = 2F_{\gamma, \gamma > 100}^\text{cascade}(E, z, L_{\gamma, \Gamma}) \times (100 \text{ MeV} / E)^{-1.5} \), which is derived by assuming that the cascade spectrum is a power-law spectrum with photon index 1.5 (Strong et al. 1974; Tavecchio et al. 2010).
The EGRB intensity in case II, which depends on the EGMF, is written as

\[ F_{\text{EGRB}}^{\text{ii}}(E) = \eta \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN}{dE} dE \int_{0}^{\tau_{\text{max}}} \frac{dV}{dz} d\Omega \times \int_{L_{\gamma, \text{min}}}^{L_{\gamma, \text{max}}} dL_{\gamma} \rho_{\gamma} F_{\gamma, \text{tl}}(E, \gamma, L_{\gamma}, \Gamma) \times e^{-\tau(z, E)} \omega \left( \frac{F_{\text{cascade}}^{\gamma, \text{ii}, >100}}{\gamma_{\text{min}}(100)} \right). \]  

(8)

In case II, to avoid the situation that the produced pair are isotropized by EGMF when the EGMF of strength is large enough, we set \( \theta_{\text{dir}} < \pi/2 \).

### 2.4 Total EGRB intensity of blazars and its contribution to the EGRB

As mentioned above, there are two possible cases (cases I and II) for the contributions from the cascade emission to the EGRB. If we only consider case I for the cascade emission (i.e. the flux of the cascade emission is lower than the LAT sensitivity), then the total EGRB intensity of blazars is given by

\[ F_{\text{EGRB}}^{\text{tot}}(E) = F_{\text{EGRB}}^{\text{i}}(E) + F_{\text{EGRB}}^{\text{ii}}(E). \]  

(9)

The cascade emission is independent of the EGMF in this case. In fact, the contribution from the cascade emission to the EGRB would include the contributions in both cases I and II (in the latter, the flux of the cascade emission is larger than the LAT sensitivity, but the angle between the redirected secondary gamma-ray photons and the line of sight is larger than the LAT PSF angle). Therefore, the total EGRB intensity of blazars is given by

\[ F_{\text{EGRB}}^{\text{tot}}(E) = F_{\text{EGRB}}^{\text{i}}(E) + [F_{\text{EGRB}}^{\text{ii}, \text{i}}(E) + F_{\text{EGRB}}^{\text{ii}, \text{ii}}(E)]. \]  

(10)

It should be noted that the cascade emission depends on the EGMF in this case.

First, we calculate the intrinsic emission, the cascade emission and the total EGRB intensities for the LDDE model of the blazar GLF. The results calculated are shown in Fig. 2. In the top panel of Fig. 2, we consider case I of the blazar cascade emission (i.e. the total intensity is given by equation 9, and the cascade emission is independent of the EGMF). The thin solid, dotted and thick solid lines represent the intrinsic, cascade and total intensities, respectively. We have found that, in case I, the contribution from the blazar cascade emission to the EGRB cannot be negligible, and it can enhance the contribution from the blazar emission to the EGRB at high energies. However, at lower energies, this contribution is negligible.

Now, we consider the contributions from the cascade emission in both cases I and II (i.e. the total intensity is given by equation 10). Because the cascade emission in case II depends on the EGMF, we calculate the intensities with different strengths of the EGMF. The results are shown in the lower panel of Fig. 2. It can be seen from the figure that the intensity of the blazar cascade emission case II increases with an increase in the strength of the EGMF, and it will reach saturation at some value of the EGMF. From our calculations, the contribution from the blazar cascade emission in case II reaches saturation when the strength of the EGMF is \( B_{\text{EGMF}} \approx 10^{-11} \) G. In case II, the contribution from the blazar cascade emission with \( B_{\text{EGMF}} < 10^{-14} \) G is negligible. This contribution becomes significant compared with the contribution from the blazar intrinsic emission at several GeV to several tens GeV with \( B_{\text{EGMF}} > 10^{-13} \) G. If the strength of the EGMF satisfies \( B_{\text{EGMF}} > 10^{-12} \) G, then the total contribution from blazars can account for the large fraction of the EGRB at several GeV to several tens GeV.

In Fig. 3, we present the results using the PLE model of the blazar GLF. It is found that the contributions from both the blazar intrinsic emission and the cascade emission in case I are significantly larger than those derived using the LDDE model of the blazar GLF. The features of the contribution from the blazar cascade emission in case II are similar to those in Fig. 2. If the strength of the EGMF...
is larger (e.g. $b_{\text{EGMF}} > 10^{-12}$ G), then the contribution from the cascade emission to the EGRB is also significant. Assuming the PLF model, the total contribution from blazars can explain the bulk of the EGRB, irrespective of the strength of the EGMF. Moreover, it seems that the model of the blazar GLF affects the contributions to the EGRB for both the cascade emission in case I and the blazar intrinsic emission.

3 DISCUSSION AND CONCLUSIONS

We have studied the effect of cascade radiation on the contribution from blazars to the EGRB using a simple semi-analytical model. In particular, we take into account the effect of the EGMF on the cascade contribution from blazars. We have found that if the strength of the EGMF is large enough ($b_{\text{EGMF}} > 10^{-12}$ G), the cascade contribution can significantly alter the spectrum of the EGRB at high energies. If the small strength of the EGMF is large enough ($b_{\text{EGMF}} < 10^{-14}$ G), then the cascade contribution is small, but it cannot be ignored (see Figs 2 and 3).

There has been little information about the strength of the EGMF up to now. Measurements of the Faraday rotation of the polarization of radio radiation from distant quasars place upper limits on the EGMF strengths at the level of $\sim 10^{-9}$ G (e.g. Kronberg 1994; Blasi, Burles & Olinto 1999). However, the possible cascade emission from resolved blazars provides a method to probe the lower bands on the EGMF (e.g. Murase et al. 2008). The lower bounds on the EGMF at the level of $10^{-18}$–$10^{-15}$ G were obtained using this method (e.g. Neronov & Vovk 2010; Tavecchio et al. 2010; Dermer et al., 2011; Dolag et al. 2011; Huan et al. 2011; Taylor et al. 2011). In this paper, we have shown that the contribution from the blazar cascade emission to the EGRB very possibly provides another method for setting the upper bands of the EGMF. In order to do so, the prerequisites are that we have the well-determined GLF and we can estimate well the contributions from other sources to the EGRB. We have shown that a possible upper bound of the EGRB is $\sim 10^{-11}$ G.

When estimating the cascade contribution to the EGRB, there is an uncertainty in the EBL model. Venters (2010) have found that the amount of cascade radiation is sensitive to the EBL model. Actually, one of the EBL models that Venters (2010) adopted is high level (Stecker, Malkan & Scully 2006) and the other is low level (Gilmore et al. 2009). However, a recent study has indicated that the EBL intensity is low (Abdo et al. 2010d), and that several commonly used EBL models are low-level models and have similar results (e.g. Finke et al. 2010; Domínguez et al. 2011). Therefore, the effect of the uncertainty of the EBL model on the contribution from the cascade emission is expected to be slight.

Based on the observed gamma-ray sample, various models of the blazar GLF have been constructed (e.g. Inoue & Totani 2009; Ajello et al. 2011; Stecker & Venters 2011). Ajello et al. (2011) have found that these models at redshift zero are relative consistent, while a significant discrepancy between these models appears at redshift one. The LDDE model that we have used here expects a smaller number of blazars compared with those expected in the models of Stecker & Venters (2011), Ajello et al. (2011) and Inoue & Totani (2009). The model of Stecker & Venters (2011) is similar to the PLE model that we have used in this paper. Actually, the determination of the blazar GLF, based solely on the observed gamma-ray sample, is not certain, because of the effect of source confusion and the active feature of blazars (Venters & Pavlidou 2011). Stecker & Venters (2011) have indicated that source confusion can lead to an underestimate of the contribution to the EGRB below 1 GeV from blazars. The active flare can bring intrinsically faint blazars to the sample of bright blazars, which flattens the faint-end slope of the observed blazar source counts. This flare effect can also cause an underestimate of the contribution. In this sense, we conclude that we cannot rule out blazar dominance of the EGRB from our calculations.

ACKNOWLEDGMENTS

We thank the anonymous referee for very constructive comments, which have substantially improved the quality of this paper. This work is partially supported by the National Natural Science Foundation of China (NSFC 10778702), a 973 Programme (2009CB824800) and the Yunnan Province under grant 2009 OC.

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