Chapter 5

Extragalactic Gamma-Ray Background

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/67335

Abstract

The origin of the extragalactic gamma-ray background (EGRB) is an important open issue in the gamma-ray astronomy. There are many theories about the origin of EGRB: (1) some truly diffuse processes, such as dark matter (DM) annihilation or decay, which can produce gamma rays; (2) gamma rays produced by energetic particles accelerated through induced shock waves during structure formation of the universe; (3) a lot of unidentified sources, including normal galaxies, starbursts and active galactic nuclei (AGNs), contain a large number of energetic particles and can emit gamma rays. Among various extragalactic sources, blazars including flat spectral radio quasars (FSRQs) and BL Lac objects are one of the most possible sources for EGRB. As continuous accumulation of the data observed by the Fermi Gamma-Ray Space Telescope, it is possible to directly construct gamma-ray luminosity function (GLF) of the blazars involving evolution information. In this chapter, based on the largest clean sample of AGNs provided by Fermi Large Area Telescope (LAT), we mainly study blazar's GLFs and their contribution to EGRB. In our study, we separately construct GLFs of FSRQs and BL Lacs and then estimate the contributions to EGRB, respectively. Further, we discuss the diffuse gamma ray from other astrophysical sources and the other possible origins of the EGRB.

Keywords: blazars, gamma-ray radiation, luminosity function, the extragalactic gamma-rays background

1. Introduction

The large area telescope (LAT [1]) onboard Fermi gamma-ray space telescope (Fermi) has measured the extragalactic diffuse gamma-ray background and then provided useful information for us to study the origins of the extragalactic gamma-ray background (EGRB) [2–5]. However, the origin of the EGRB is still an unsolved problem. Observationally, an isotropic component of the EGRB emission was first detected by the SAS-2 satellite [6, 7] and subsequently measured by the energetic gamma-ray experiment telescope (EGRET) [8–10]. Due to the higher sensitivity of Fermi-LAT than that of EGRET, the observed integrated flux above 100 MeV by the LAT is

$(1.03\text{–}0.17)\times 10^{-5}$ photons $cm^{-2}s^{-1}$ [3], which is lower than $(1.14\text{–}0.05)\times 10^{-5}$ photons $cm^{-2}s^{-1}$ measured by EGRET [11]. Recently, Fermi-LAT has made a new measurement of the EGRB spectrum and their results shown that the EGRB energy spectrum between 0.1 and 820 GeV is to be well represented by a power law with an exponential cutoff above 300 GeV [5]. **Figure 1** (left panel) shows the measured X-ray and gamma-ray background radiation spectra. We know that the X-ray background spectrum has no big change with time and has been considered as the integrated light produced via the accretion process of active galactic nuclei (AGNs) [12]. However, the gamma-ray spectrum is different from the X-ray background spectrum due to the sensitivity of an instrument and other reasons. Before the Fermi gamma-ray space telescope era, neither spectrum nor origin of the EGRB was well understood. In particular, the spectrum at 0.03–50 GeV reported by EGRET has a break in the several GeV. With the arrival of Fermi era, more accurate determination of the EGRB spectrum and more extragalactic source samples are provided to understand the nature of the EGRB. Note that the whole gamma-ray sky contains diffuse galactic emission, point sources, isotropic extragalactic diffuse emission and local and solar diffuse emissions. **Figure 1** (right panel) shows that the EGRB spectrum is obtained by removing the resolved point source, like as the most recent list of resolved Fermi-LAT source (3FGL), the diffuse galactic emission determined by GALPROP, which simulates both cosmic-ray propagation in the galaxy and the gamma-ray flux resulting from interactions and possibly an isotropic flux of galactic, by restricting data to regions with $|b| > 10°$ or even higher galactic latitudes.

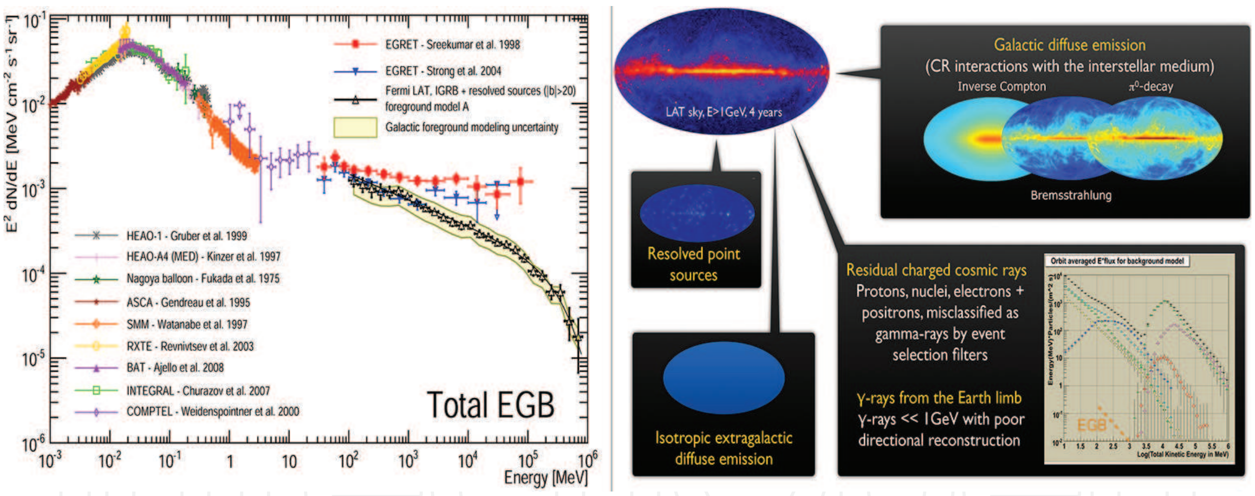

Figure 1. Left: The measured X-ray and gamma-ray background radiation spectra, which is from Ref. [5]. Right: The composition of the total gamma-ray flux. The figure is obtained from the report of Ackermann, M. at Fermi Symposium.

Similar to the extragalactic EGRET sky, blazars are the largest source class identified by Fermi extragalactic sky and their contribution to the EGRB has been widely discussed. Typical estimated contributions of unresolved blazars to the EGRB range from 10 to 100% [13–36]. Blazars are divided into two main subgroups: BL Lac objects and FSRQs [37]. Among the gamma-ray blazar sample, the number of FSRQs detected by Fermi-LAT is smaller than that of BL Lac objects (e.g., 2FGL, 3FGL). FSRQs generally show softer spectrum in the gamma-ray band (e.g., [38]), which is to be detected harder than BL Lac objects at a given significant limit. On the one hand, BL Lacs are reputed as the population of extragalactic sources that show a negative or no cosmological evolution [39–42], but FSRQs are regarded as those with a positive cosmological evolution, which is similar to the population of X-ray-selected, radio-quiet AGNs [43–45]. Ajello et al. [32] suggested that BL Lacs have a more complex evolution. At the modest redshift region, most BL Lac classes show a positive evolution with a space density peaking. Meanwhile, their results suggest that the evolution of low-luminosity, high-synchrotron-peaked (HSP) BL Lac objects is strong negative with number density increasing for low redshift range ($z \leq 0.5$). In addition, the contributions of the EGRB from other sources or processes are very important. Those are star-forming galaxies [46, 47], radio galaxies (e.g., [14, 46, 48]), gamma-ray bursts (GRBs) (e.g., [49]), high galactic-latitude pulsars (e.g., [50]), intergalactic shocks (e.g., [51, 52]), Seyferts (e.g., [53]), cascade from ultra-high-energy cosmic rays (e.g., [54, 55]), large galactic electron halo [56], cosmic-ray interaction in the solar system [57] and dark matter annihilation or decay (e.g., [58]). Recently, with the assumptions and uncertainties, Ajello et al. [33] and Di Mauro and Donato [36] shown that the EGRB can be fully accounted for the sum of contributions from undetected sources including blazars and radio and star-forming galaxies. Those results imply that little room in space is left for other processes such as shock wave or DM interactions (e.g., [33, 59]).

The extragalactic gamma-ray sky provides an amount of gamma-ray sources and allows us to obtain the information about the evolution of sources and estimate their contributions to the EGRB. Because the blazar's contribution is the main content of research on this chapter, the detail about how to build the gamma-ray luminosity function (GLF) will be discussed in Section2. In Section3, a brief description about how to estimate different components' contributions to the EGRB is given and finally, we give the conclusions and discussions in Section4.

2. The gamma-ray luminosity function

Since the Fermi-LAT has detected and identified more and more gamma-ray sources and observed previously detected objects in greater detail, the method by using the gamma-ray luminosity function (GLF) to estimate the EGRB of resolved sources has become much more reliable. In this approach, the GLF involving the evolution of redshift as well as the distribution of spectral indices of a given source class can be established for all known sources and the observed population can be extrapolated to lower fluxes.

2.1. Function derivation

As professed in Ref. [31], there is a classical approach to obtain the luminosity function, which is on account of 1/VMAX method provided by Schmidt [60] to deal with redshift bins. However, this method has a fault, which is known to introduce bias in each binning. For a small sample and/or a large span of parameters, if the bins contained significant evolution, the method would result in a loss of important information. In order to constrain the model parameters for various models of the evolving GLF, a maximum likelihood method is adopted, which is first introduced by Marshall et al. [61]. The likelihood function L is given as follows (e.g., [17, 19, 24, 62]):

$$\mathcal{L} = \exp(-N_{\exp})\prod_{i=1}^{N_{obs}}\Phi(L_{\gamma,i},\ z_i,\ \Gamma_i), \tag{1}$$

where $N_{\exp}$ is the expected number of source detections:

$N_{\rm exp} = \int d\Gamma \int dz \int dL_\gamma \Phi(L_{\gamma,i}, z_i, \Gamma_i)$, $N_{\rm exp}$ is the number of the sample of sources and $\Phi(L_{\gamma,i}, z_i, \Gamma_i)$ is the distribution function of the space density of source on luminosity (L_γ), redshift (z) and photon index (Γ). The function form can be expressed as follows:

$$\Phi(L_{\gamma,i},\ z_i,\ \Gamma_i) = \frac{d^3N}{dL_\gamma dz d\Gamma} = \rho_\gamma(L_\gamma,\ z) \times \frac{dN}{d\Gamma} \times \frac{dV}{dz} \times \omega(L_\gamma,\ z,\ \Gamma), \tag{2}$$

where $\rho_\gamma(L_\gamma, z)$ is the γ-ray luminosity function and dV/dz is the comoving volume element per unit redshift and unit solid angle:

$dV/dz = cd_L^2/(H_0(1+z)^2\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda})$. $dN/d\Gamma$ is the intrinsic photon index distribution assumed as a Gaussian $\exp(-(\Gamma-\mu)^2/2\sigma^2)$, where μ and σ are the mean and the dispersion, respectively. $\omega(L_\gamma, z, \Gamma)$ is the detection efficiency and represents the probability of detecting an object with the γ-ray luminosity L_γ at redshift z and photon index Γ [1, 24, 31]. The relationship between χ^2 and likelihood (L) can be expressed by function $\chi^2 = -2\ \ln\ (L)$ [63]. In this case, the function $\chi^2 = -2\ \ln L$ that is minimized is defined as follows:

$$\chi^2 = -2\sum_i^{N_{obs}} \ln(\Phi(L_{\gamma,i}, z_i, \Gamma_i)) + 2N_{\rm exp}. \tag{3}$$

For a given GLF, the redshift distribution, luminosity distribution and photon index distribution can be divided into three intervals of size $dL_\gamma dz d\Gamma$ and the three kinds of differential distributions can be expressed from GLF as follows [31]:

$$\begin{aligned} \frac{dN}{dz} &= \int_{\Gamma_{min}}^{\Gamma_{max}} \int_{L_{\gamma,min}}^{L_{\gamma,max}} \frac{d^3N}{dL_\gamma dz d\Gamma} dL_\gamma dz, \\ \frac{dN}{dz} &= \int_{\Gamma_{min}}^{\Gamma_{max}} \int_{z_{min}}^{z_{max}} \frac{d^3N}{dL_\gamma dz d\Gamma} dz d\Gamma, \\ \frac{dN}{dz} &= \int_{\Gamma_{min}}^{\Gamma_{max}} \int_{L_{\gamma,min}}^{L_{\gamma,max}} \frac{d^3N}{dL_\gamma dz d\Gamma} dL_\gamma dz, \end{aligned} \tag{4}$$

The source count distribution can be derived as follows:

$$\begin{aligned} \mathrm{N}\ (> S) &= \int_{\Gamma_{\rm min}}^{\Gamma_{\rm max}} d\Gamma \int_{z_{\rm min}}^{z_{\rm max}} dz \int_{L_\gamma(z,S)}^{L_{\gamma,\ \rm max}} dL_\gamma\ \frac{d^3N}{dL_\gamma dz d\Gamma} \\ &= \int_{\Gamma_{\rm min}}^{\Gamma_{\rm max}} \frac{dN}{d\Gamma} d\Gamma \int_{z_{\rm min}}^{z_{\rm max}} \frac{dV}{dz} \int_{L_\gamma(z,S)}^{L_{\gamma,\ \rm max}} \rho_\gamma(L_\gamma, z)\omega(L_\gamma,\ z,\ \Gamma) dL_\gamma \end{aligned} \tag{5}$$

where $L_\gamma(z, S)$ is the luminosity of a source at redshift z with a flux of S_γ (>100 MeV).

Through minimized Eq. (3), we can obtain the best-fitting parameters of the models. There are multiple parameters in our various models to find the best in observational data in a multidimensional model parameter space; the MCMC technique can be employed for its high efficiency to constrain the model parameters. In this method, the Metropolis-Hastings algorithm that generates samples from the posterior distribution using a Markov Chain is used when sampling the model parameters and the probability density distributions of the model parameters are asymptotically proportional to the number density of the sample points. For each parameter set P, one obtains the likelihood function $L(P) \propto \exp\left(-\chi^2(P)/2\right)$, where χ^2 is obtained by comparing model predictions with observations. A new set of parameter $P^{'}$ is adopted to replace the existing one P with a probability of min $\{1, L(P^{'})/L(P)\}$. The MCMC method has been reviewed by Fan et al.[64] and described in detail by Neal [65], Gamerman [66], Lewis and Bridle [67], Mackay [68].

2.2. Models description

The GLF models for different source classes are uncertainty. Currently, there are two methods for constructing the blazars' GLF: the first method is to build the GLF by assuming a relationship between the GLF and the luminosity function in a lower energy band, for example, that the GLF relates to radio luminosity function (RLF) or to the X-ray luminosity function (XLF) (e.g., [14, 16, 17, 19, 23, 28, 48, 69–72]); the second method is to construct the GLF directly using observed gamma-ray data of blazars (e.g., [15, 17, 22]). Before the Fermi era, constructing the GLF model indirectly was used more frequently due to the small EGRET samples, which results in blazar's contribution between the range of 10 and 100%. In next sections, we briefly review those models for directly constructing the GLF.

2.2.1. The pure density evolution

The pure density evolution (PDE) model is the simplest scenario of evolution and the GLF has a following form:

$$\rho(L_\gamma, z) = \frac{A}{\ln(10)L_\gamma}\left[\left(\frac{L_\gamma}{L}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L}\right)^{\gamma_2}\right]^{-1} \times e(z), \tag{6}$$

where $e(z) = (1+z)^\kappa$ is the standard power-law evolutionary factor. In this case, there are five model parameters and other two parameters, μ and σ, are also added.

2.2.2. The pure luminosity evolution

In the pure luminosity evolution (PLE) model, the GLF can be expressed as follows:

$$\rho(L_\gamma,\ z) = \frac{A(1+z)^\kappa e^{z/\xi}}{\ln(10)L_\gamma}\ \left[\left(\frac{L_\gamma}{L_*(1+z)^\kappa e^{z/\xi}}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*(1+z)^\kappa e^{z/\xi}}\right)^{\gamma_2}\right]^{-1}, \tag{7}$$

where A is a normalization factor, L_i is the evolving break luminosity, γ_1 is the faint-end slope index, γ_2 is the bright-end slope index, κ and ξ represent the redshift evolution. Including the parameters μ and σ, there are 8 parameters in calculations.

2.2.3. The luminosity-dependent density evolution

In the luminosity-dependent density evolution (LDDE) model, the GLF evolution is decided by a redshift cutoff that depends on luminosity and the GLF can be given by

$$\rho(L_\gamma,\, z) = \frac{A}{\ln(10)L_\gamma}\left[\left(\frac{L_\gamma}{L_*}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*}\right)^{\gamma_2}\right]^{-1}$$
$$\left[\left(\frac{1+z}{1+z_c^*(L_\gamma/10^{48})^\alpha}\right)^{p_1} + \left(\frac{1+z}{1+z_c^*(L_\gamma/10^{48})^\alpha}\right)^{p_2}\right], \tag{8}$$

where A is a normalization factor, L is evolving break luminosity, γ_1 and p_1 are the faint-end slope index, γ_2 and p_2 are the bright-end slope index, z_c is redshift peak with a luminosity (here 10^{48} ergs s^{-1}) and α is power-law index of the redshift-peak evolution. From this, there are 10 parameters for calculation.

The detailed description about PLE and LDDE models can be found in sections4.1 and 4.2 from Ref. [32]. These models also can be applied to X-ray band, to determine the information of evolution of sources in X-ray band (e.g., [62]). With the increase in the number of the detected sources, the evolutionary form of those sources becomes more complicated and the updated forms of those models can be found in Ref. [33], which allows the Gaussian mean μ of the photon index and the evolutionary factor $e(z, L_\gamma)$ to change with luminosity.

2.3. The cosmological evolution

In Fermi sample, the large redshift range between $z = 0$ and $z = 3.1$ of gamma-ray blazars was found. The obtained GLFs have shown that blazars have a cosmological evolution in their gamma-ray band. We have simply discussed the redshift evolution of blazars in the "Introduction". Ajello et al. [32] recently have presented the new results on the cosmological evolution of the BL Lac population by using the largest and most complete sample of gamma-ray BL Lacs available in the literature and they found that for most BL Lac classes, the evolution is positive, with a space density peaking at modest redshift (z≈1.2) (see **Figure 2**). In **Figure 2**, we also see that for their higher luminosity, FSRQs dominate at all redshifts z > 0.3 and the extreme growth in BL Lac numbers at low z allows them to produce ~90% of the local luminosity density. In particular, low-luminosity, high-synchrotron-peaked (HSP) BL Lac objects showed different evolutionary behaviors with respect to other blazar classes (see **Figure 2**). They have strong

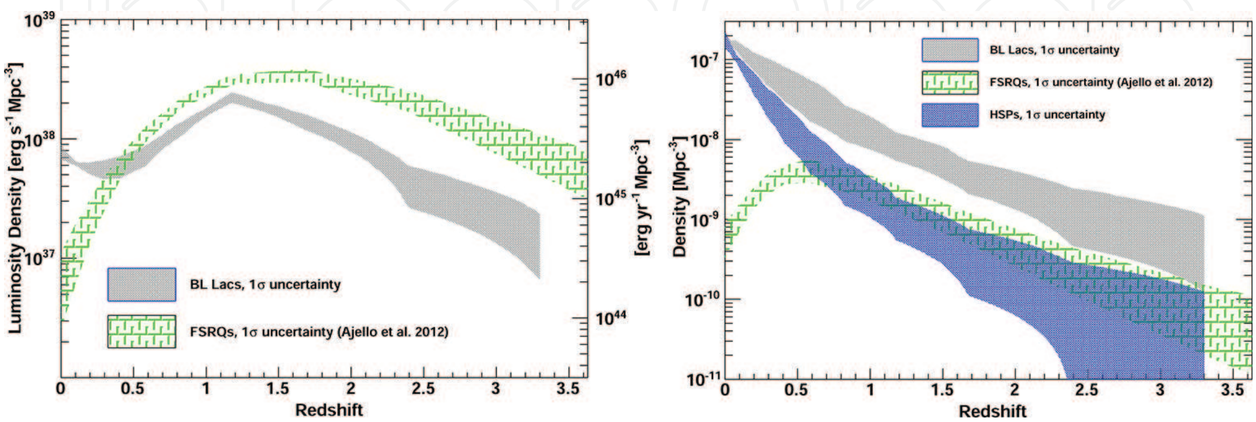

Figure 2. Left: The evolution of the luminosity density of FSRQs compared to that of BL Lac objects. Right: Number density of FSRQs, BL Lac objects and HSPs. The figures are obtained from the report of [32] and see Ref. [32] for additional details.

negative evolution with number density increasing for z<0.5, which confirms previous standpoints of negative evolution based on the samples of X-ray-selected BL Lac objects and this sample contained a large fraction of HSPs [39, 41].

3. The extragalactic gamma-ray background

The origin of the EGRB has been widely discussed for various gamma-ray-emitting sources in literature. Fermi has observed gamma-ray emission from blazars, star-forming galaxies, radio galaxies, GRBs and high-latitude pulsars. Ajello et al. [33] and Di Mauro and Donato [36] suggested that blazars, star-forming galaxies and radio galaxies are the main contributors to the EGRB. For those emitting sources, we focus on how to estimate the contribution of unresolved objects to the EGRB below, based on the best-fitting GLF (space density of sources).

The differential intensity of the EGRB radiation can be expressed as follows:

$$\frac{dN}{dEd\Omega} = \int_{\Gamma_{min}}^{\Gamma_{max}} d\Gamma \frac{dN}{d\Gamma} \int_{z_{min}}^{z_{max}} \frac{dV}{dz} \int_{L_{\gamma,min}}^{L_{\gamma,max}} dL_{\gamma}$$
$$\Phi(L_\gamma, z) F_\gamma^{intrinsic}(E, L_\gamma, z, \Gamma) e^{-\tau(E,z)} \left(1.0 - \omega(L_\gamma, z, \Gamma)\right) \tag{9}$$

where $\Phi(L_\gamma, z)$ is the GLF and $e^{-\tau(E,z)}$ is the optical depth of the extragalactic background light (EBL) for the sources at redshift z emitting gamma-ray photon energy E. Recently, there are many studies on EBL (e.g., [21, 73–75]). Generally, we adopted the model given by [73] for the EBL to calculate the optical depth. In Eq. (9), $F_\gamma^{intrinsic}(E, L_\gamma, z, \Gamma)$ represents the intrinsic photon flux at energy E with γ-ray luminosity L_γ and a power-law spectrum at redshift z and it is expressed as follows:

$$F_\gamma^{\rm intrinsic}(E,\ L_\gamma,\ z,\ \Gamma) = \frac{L_\gamma\ (1+z)^{2-\Gamma}}{4\pi d_L^2 E_1^2} \begin{cases} (2-\Gamma)\left[\left(\frac{E_2}{E_1}\right)^{2-\Gamma} - 1\right]^{-1} \left(\frac{E}{100\ \rm MeV}\right)^{-\Gamma} & \Gamma \neq 2, \\ \dfrac{1}{\ln(E_2/E_1)} \left(1 - \dfrac{E_1}{E_2}\right)^{-1} \left(\dfrac{E}{100\ \rm MeV}\right)^{-2} & \Gamma = 2, \end{cases} \tag{10}$$

where $E_1 = 100$ MeV and $E_2 = 100$ GeV. Therefore, the integrated intensity between photon energy E_1 and E_2 $(E_2 > E_1)$ can be written as follows:

$$\frac{dN}{d\Omega} = \int_{E_1}^{E_2} \frac{dN}{dEd\Omega} dE \tag{11}$$

The electrons and positrons are produced due to the interaction between very high energy (VHE) photons from TeV sources and ultraviolet-infrared photons of EBL. The pairs could scatter the cosmic microwave background (CMB) radiation to high-energy background radiation through the inverse Compton scattering process (e.g., [76–83]). This cascading emission is regarded as a contributor to the EGRB if the flux of the cascade flux is lower than the detector's sensitivity. Now, we consider only the first generation of the electron-positron pairs produced by the gamma-ray absorption to obtain the cascade emission because the emission from the second generation or more than second generation of created pairs can be negligible at the GeV band [21]. The formulation of the cascade flux is given as follows [84]:

$$F_{\gamma}^{\text{cascade}}(E,\ L_{\gamma},\ z,\ \Gamma) = \frac{81\ \pi}{16\ \lambda_c^3}\ \frac{\varepsilon_c^2 m_e c^2}{(1+z)^4 U_{\text{CMB}}} \int\limits_{\sqrt{3\varepsilon_c/4\varepsilon_{\text{CMB}}(1+z)}}^{\infty} \frac{d\gamma}{\gamma^8 \exp[3\varepsilon_c/4\gamma^2\varepsilon_{\text{CMB}}(1+z)-1]} \times \int\limits_{2\gamma}^{\varepsilon_{\max}} d\varepsilon\ F_{\text{VHE}}^{\text{intrinsic}}\left(\frac{5.11\times10^5}{10^6}\varepsilon,\ z,\ L_{\gamma},\ \Gamma\right)[1-e^{-\tau(\varepsilon,z)}] \tag{12}$$

where $\lambda_c = 2.426\times10^{-10}$ cm is the Compton length, the dimensionless energy $\varepsilon_c = E\times10^6/(5.11\times10^5)$, $U_{CMB} = 4.0\times10^{-13}$ erg cm^{-3} is the CMB energy density at $z = 0.0$, $\varepsilon_{CMB} = 1.24\times10^9 m_e c^2$ is the average CMB photon energy at $z = 0.0$ and $\varepsilon_{CMB} = 2.0\times10^8$ corresponding to $E_{VHE} = 100TeV$. $F_{VHE}^{intrinsic}(E_{VHE}, L_\gamma, z, \Gamma)$ represents the possible intrinsic TeV spectrum, which is extrapolated to the TeV energy ranges from the observed GeV spectrum Eq. (10) by assuming a power-law spectrum. In Eq. (9), using Eq. (12) in place of Eq. (10) allows us to compute the contribution to the EGRB from the cascade emission of the source.

It is noted that there are two possible contributions for the cascade emission to the EGRB because the pairs are deflected by the extragalactic magnetic field (EGMF), which is shown in **Figure 3**. In case I, the cascade emission can contribute to the EGRB if the flux of the cascade emission is lower than that of the LAT sensitivity. In case II, although the flux of the cascade emission is larger than that of the LAT sensitivity, the angle between the redirected secondary gamma-ray photons and the line of sight is larger than that of the LAT point-spread function (PSF) (i.e., $\theta > \theta_{PSF}$). Thus, the cascade emission will not be attributed to a point source by the LAT and it then contributes to the EGRB, where $\theta_{PSF} = (1.7\pi/180)(0.001E)^{-0.74}[1 + (0.001E/15)^2]^{0.37}$ [85]. For more detailed information, see Refs. [81, 84].

3.1. Blazars

Blazars emit gamma rays via the inverse Compton scattering processes and/or hadronic processes and dominate extragalactic gamma-ray sources. Therefore, it is naturally expected that blazars contribute the main EGRB. However, its fraction was very uncertain in the EGRET era due to its small samples. At the same time, its fraction also severely depends on GLF. Blazars are divided into two main subgroups: BL Lac objects and FSRQs [37]. **Figure 4** shows FSRQs' EGRB spectra with LDDE model and BL Lacs' EGRB spectra with PDE model. Compared to FSRQs, BL Lacs have lower gamma-ray luminosities, lower redshifts and harder spectral indices in statistics (e.g., [86]). Thus, BL Lacs can provide a significant part in the contribution of blazar to the EGRB above 10GeV. From **Figure 4**, we find out that the cascade emission from BL Lacs has a rather large fraction of the total EGRB energy flux and contrary to that of FSRQs, which may be caused by harder spectrum for BL Laces. Therefore, the contribution from BL Lacs cascade emission to the EGRB cannot be negligible. Based on the effect of the EGMF on the cascade contribution from blazars, Yan [84] have studied the effect of cascade radiation on the contribution to the EGRB using a simple semi-analytical model. They suggested that if the strength of the EGMF is large enough ($B_{EGMF} > 10^{-12}$ 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 ($B_{EGMF} < 10^{-14}$ G), then the cascade contribution is small, but it cannot be ignored. Recently, Ajello et al. [33] used an updated GLFs to analyze the redshift, luminosity and photon index distributions and obtained the best-fitting evolutionary parameters of the GLFs. According to the GLFs and spectral energy distribution (SED) model consistent with the Fermi blazar observations, their result shown that blazars account for 50^{+12}_{-10} to the EGRB (see **Figure 5**).

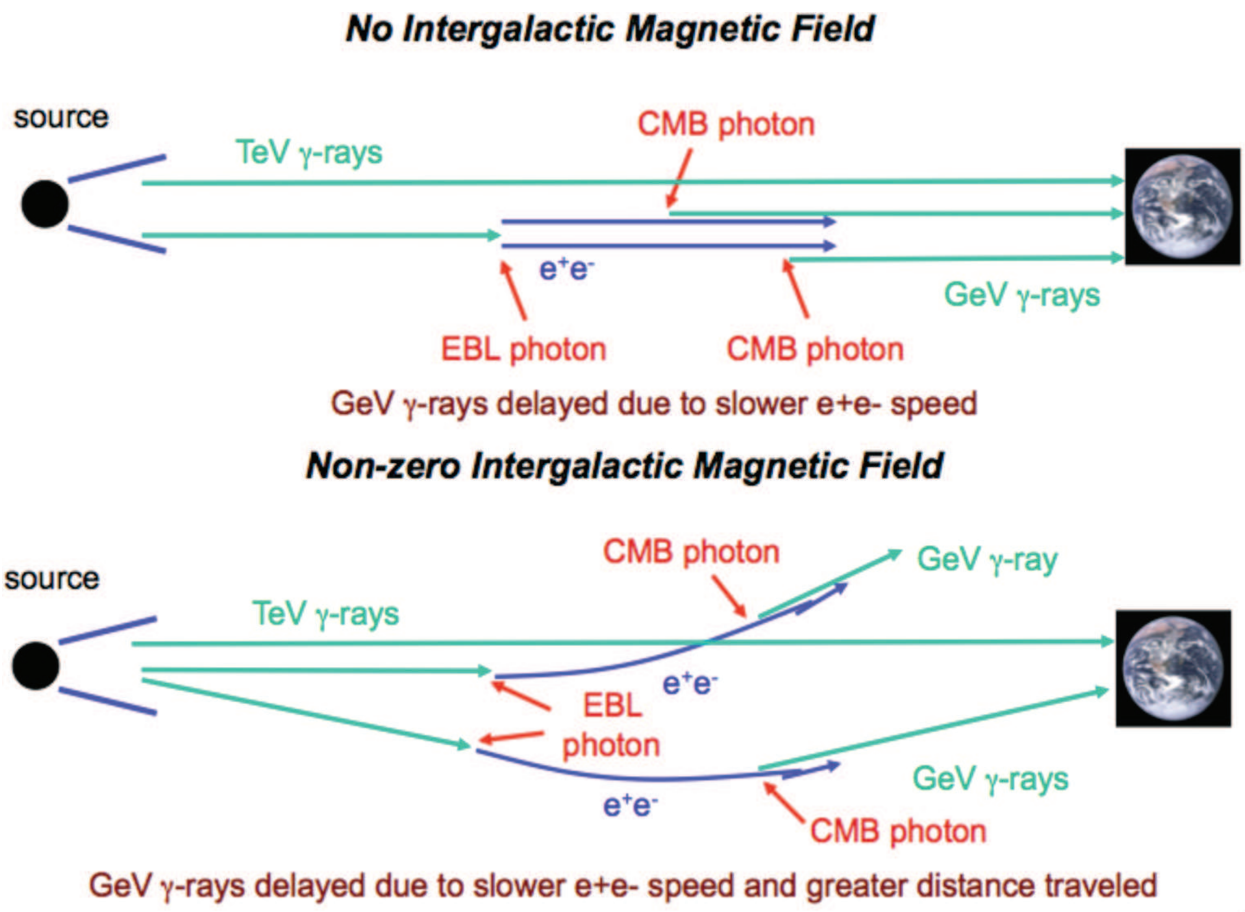

Figure 3. The cascade radiation processes in no or non-zero extragalactic magnetic field (EGMF). Note that the pairs produced by the interaction between very high energy (VHE) photons and ultraviolet-infrared photons of EBL are detected by the EGMF. The figures are obtained from the report of Marco Ajello at Fermi Symposium.

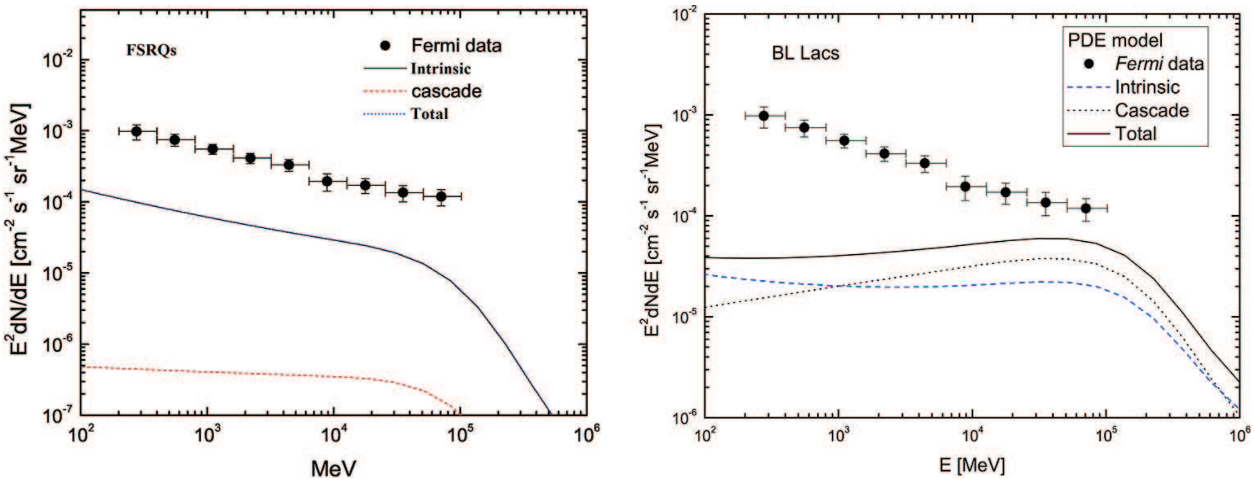

Figure 4. Comparison of predicted EGRB spectra from FSRQs and BL Lacs with the observed data of blazars. Note that the EGRB spectra from FSRQs and BL Lac are estimated based on LDDE and PDE models, respectively. The two figures are obtained from the report of Refs. [29, 30].

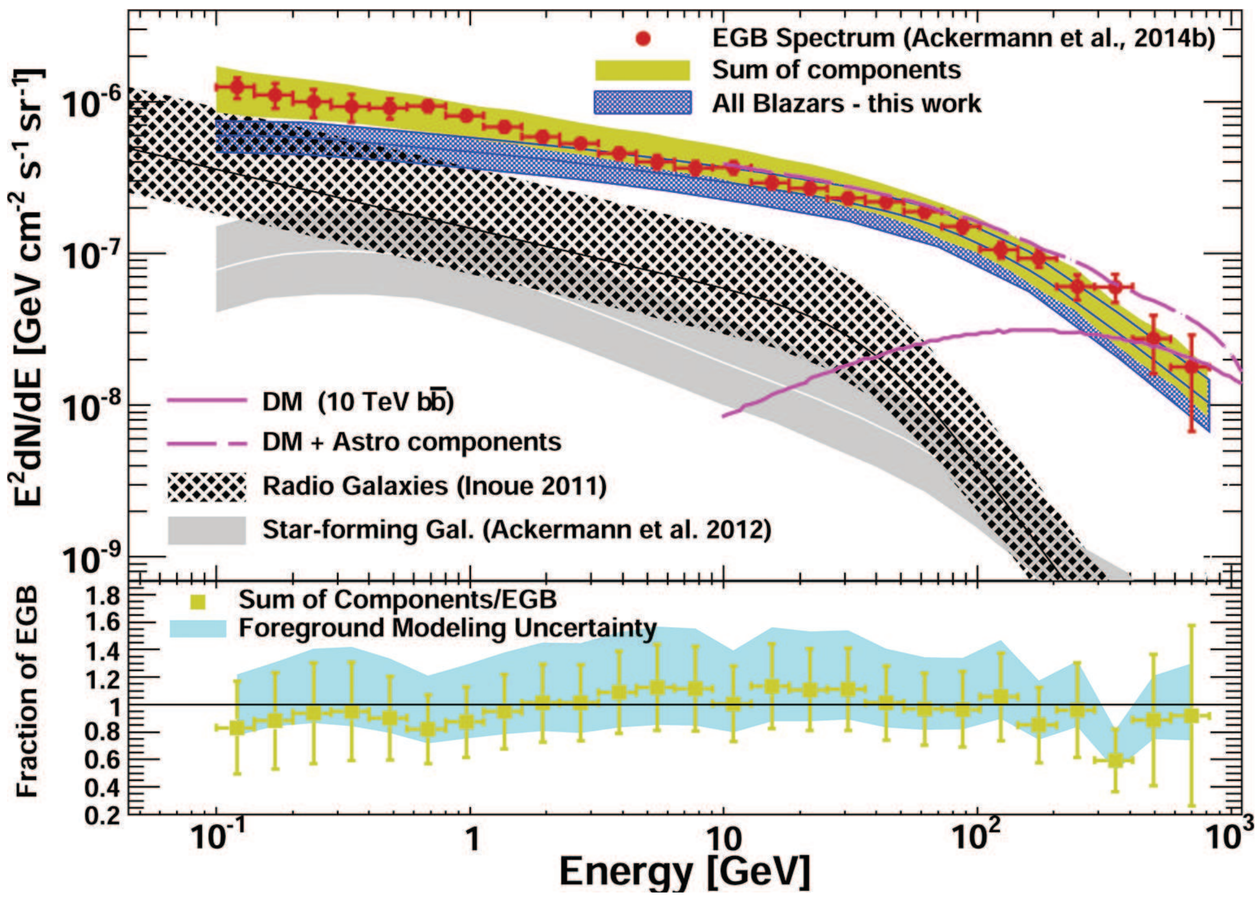

Figure 5. The EGRB spectrum of blazars [33], star-forming galaxies (gray band [4]) and radio galaxies (black striped band [48]) as well as summation of these three populations (yellow band), compared to the intensity of the observed ERGB [5]. The figure is obtained from the report of Ref. [33].

3.2. Radio galaxies

Radio galaxies are one of the largest subclasses of radio-loud AGNs. It is more in number than blazars in the entire sky. Even though radio galaxies are fainter than blazars, Fermi-LAT has just detected gamma rays from ~15 extragalactic sources, including 12 FR Is and 3 FR IIs [87]. In order to estimate the contribution to the EGRB from radio galaxies, their GLF is required. We must obtain indirectly the GLF due to the limited Fermi radio galaxy samples. Relying on a correlation between the luminosities in the radio and gamma-ray frequencies, Inoue [48] converted the RLF [88] into the GLF and estimated about 25% of EGRB can be solved by radio galaxies (see **Figure 5**). This uncertainty significantly depends on the limited sample and the errors between the gamma ray and radio luminosity correlation.

3.3. Star-forming galaxies

The Fermi-LAT has detected gamma-ray from ~9 star-forming (SF) galaxies [2]. Those gamma rays are produced by interactions between cosmic rays and gas or interstellar radiation fields, including the decay of neutral pion and electron interactions (bremsstrahlung and inverse Compton scattering). Similar to radio galaxies, it is not straightforward to construct the GLF because of the limited star-forming galaxy sample. Generally, the correlations between the IR wavelength and gamma-ray region are used to predict the gamma-ray diffuse emission for the unresolved SF galaxy population. Different from other types of source, the SF gamma-ray average spectrum is difficult to firmly establish due to the paucity of statistics. Milky Way-like SF galaxies (MW model) and an assumed power-law spectrum (PL model) are proposed by Ackermann et al. [89] to express an average spectrum of SF Galaxies. In particular, the two predictions are different above 5 GeV, where the MW model softens significantly. Therefore, using the correlation between infrared and gamma-ray luminosities, based on the well-established infrared luminosity functions and the SF gamma-ray average spectrum, the GLF of star-forming galaxies is well built and the contribution of star-forming galaxies to the EGRB can be estimated as 10–30% of the EGRB at >0.1 GeV [89], which can be seen in **Figure 5**.

It should be noted that about 95% of the EGRB can be naturally explained by blazars, star-forming galaxies and radio galaxies in the 0.1–820 GeV range. Only modest space is left for other diffuse processes such as dark matter interactions, which suggests that other gamma-ray-emitting sources' contribution can be neglected. Ajello et al. [33] also concluded that the result of their simulation gave an upper limit on DM self-annihilation cross sections, which is similar to that from the independent types of analysis (e.g., [59]).

4. Conclusion and discussion

In this chapter, we reviewed the origin of EGRB and estimated the contribution of unsolved gamma-ray-emitting sources from Fermi-LAT to the EGRB based on the construction of the corresponding GLFs. Since Fermi-LAT has higher sensitivity and provides numerous gamma-ray-emitting sources for studies, we found two important results: (i) the redshift evolutionary information of gamma-ray sources, particularly for blazars; HBLs show strong negative cosmological evolution, while FSRQs and luminous BL Lacs show positive evolution like as Seyferts and the cosmic star formation history. (ii) Fermi sources' contribution to the EGRB; blazars clearly contribute to most of the EGRB (≈40-62%), as well as radio galaxies and star-forming galaxies can occupy for the rest room of the EGRB [33, 36]. These results suggest that the contributions of other emitting sources have only little space to the EGRB. However, the uncertainties associated with these predictions from radio galaxies and star-forming galaxies are still quite large because of the small samples. This situation is very similar to blazar studies in the early EGRET era. Therefore, further data will be required to construct the GLFs and precisely evaluate the contributions from those two populations.

Now, there are still some unresolved problems. We have not seen the signature of dark matter particles in the EGRB spectrum, although they are considered as the possible origin of EGRB. As we known, Fermi-LAT has accurately measured the EGRB spectrum and the anisotropy of the EGRB [4] and the emission from dark matter is anisotropic and its spatial pattern is unique and predictable [90]. Therefore, we can obtain an upper limit on the annihilation cross section by comparing the expected EGRB angular power spectrum from dark matter annihilation with the measured spectrum. The work of Ajello et al. [33] shown that an analysis of the EGRB and its components can constrain diffuse emission mechanisms such as DM annihilation. Di Mauro and Donato [36] probed a possible emission coming from the annihilation of WIMP DM in the halo of our galaxy and found that the DM component can very well fit the EGRB data together with the realistic emission from a number of unresolved extragalactic sources.

The value of the EGMF has still not been determined. Since the pairs scatter CMB photons to GeV energies by Compton mechanism for cascade process around a TeV sources, Fermi-LAT could measure those GeV photons, which would give a straight measurement of the EGMF. As continuous accumulation of the data observed and the further development of detection equipment, the imprint of the EGMF may be found in the gamma-ray spectrum and/or flux [79, 80, 91]. The EGMF imprint might also be found in the angular anisotropy of the EGRB [92]. If the effect of cascade depending on the EGMF cannot be neglected [84], the electron-positron pairs produced in cascade process could be deflected by a high value of the EGMF, which makes GeV photons more isotropic. Therefore, the EGRB spectrum with the anisotropy could probe the strength of EGMF [87].

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http://dx.doi.org/10.5772/67335

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