The Cosmological Evolution of Blazars and the Extragalactic Gamma-Ray Background in the Fermi Era

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The latest determination of the extragalactic gamma-ray background (EGRB) radiation by Fermi is compared with the theoretical prediction of the blazar component by Inoue & Totani (2009; hereafter IT09). The Fermi EGRB spectrum is in excellent agreement with IT09, indicating that blazars are the dominant component of the EGRB, and contributions from any other sources (e.g., dark matter annihilations) are minor. It also indicates that the blazar SED (spectral energy distribution) sequence taken into account in IT09 is a valid description of mean blazar SEDs. The possible contribution of MeV blazars to the EGRB in the MeV band is also discussed. In five total years of observations, we predict that Fermi will detect $\sim$1200 blazars all sky down to the corresponding sensitivity limit. We also address the detectability of the highest-redshift blazars. Updating our model with regard to high-redshift evolution based on SDSS quasar data, we show that Fermi may find some blazars up to $z \sim 6$ during the five-year survey. Such blazars could provide a new probe of early star and galaxy formation through GeV spectral attenuation signatures induced by high-redshift UV background radiation.

I. INTRODUCTION

The origin of the extragalactic diffuse gamma-ray background (EGRB) is a long-standing puzzle. First discovered by the SAS 2 satellite [1, 2], its existence was subsequently confirmed up to $\sim 50$ GeV by EGRET (Energetic Gamma-Ray Experiment Telescope) on board the Compton Gamma Ray Observatory. EGRET measured a flux of about $1 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ above 100 MeV and an approximately power-law spectrum with photon index of $\sim -2$ over the wide range of 30 MeV - 50 GeV [3-4]. Very recently, Ref. [5] reported Fermi observations of the EGRB spectrum up to 100 GeV, which connects smoothly to the EGRET results below $\sim 200$ MeV [4]. However, above this energy, the spectrum is discrepant from EGRET, being a single power-law with index $\sim -2.4$, and showing no signs of a GeV excess.

Although different types of gamma-ray sources (e.g., clusters of galaxies or dark matter annihilations) have been proposed to be significant contributors to the EGRB [see, e.g., Ref. [6] and references therein], active galactic nuclei (AGNs) of the blazar class are considered the primary candidates, since almost all of the extragalactic sources detected by EGRET were blazars. The blazar contribution to the EGRB has been estimated by numerous authors, who have reached different conclusions using different approaches, ranging from 20% to 100% of the observed flux [6-18].

In most past studies, the spectral energy distributions (SEDs) of the blazars were assumed to be power laws for all objects. In such models, it is obvious that the predicted EGRB spectrum is mainly determined by the assumed power-law indices. However, multi-wavelength observational studies indicate the existence of a non-trivial trend among blazar SEDs: the energies of the two characteristic spectral peaks in blazar SEDs (each likely reflecting the synchrotron and inverse Compton emission) systematically decrease as the bolometric luminosity increases $[19-25]$. This is often referred to as the blazar SED sequence. Although its validity is currently still a matter of debate (e.g., Ref. [24, 25, 27]), one can make a non-trivial prediction of the EGRB spectrum if this blazar sequence is assumed.

Here we compare the latest Fermi EGRB results with our model predictions, previously published in
Ref. [28] (IT09) before the former was announced. IT09 calculated the EGRB from blazars by constructing a blazar gamma-ray luminosity function (GLF) model that is consistent with the flux and redshift distributions of the EGRET blazars, accounting for the blazar sequence as well as the luminosity-dependent density evolution (LDDE) scheme that describes well the evolution of the X-ray luminosity function (XLF) of AGNs. By introducing the blazar SED sequence, we were able to make a reasonable and non-trivial prediction of the EGRB spectrum that can be compared with observations including the new Fermi data.

Recently, Ref. [28] has shown that the EGRB in the MeV band can be naturally explained by normal (i.e., non-blazar) AGNs that compose the cosmic X-ray background. If so, they should also contribute to the EGRB at \( \lesssim 1 \) GeV. We will investigate what fraction of the observed EGRB can be explained by the sum of the blazar and non-blazar AGN components. The contribution of blazars to the EGRB in the MeV band is also discussed and compared with a recent study on the possible relevance of the so-called “MeV blazars” [29].

We will then make quantitative predictions for the Fermi Gamma-ray Space Telescope [30] for its five-year survey. The first Fermi catalog for bright gamma-ray sources including AGNs has recently been released [31, 32]. The number of currently detected blazars is about 100, larger than that of EGRET by a modest factor of about 2. We limit the discussion of the blazar data to only the EGRET sample in this work, to be considered as a theoretical prediction from the pre-Fermi era. In the future, a much larger number of blazars should be detected with Fermi, which can be compared further with our predictions.

We also discuss the highest-redshift blazars detectable by Fermi, by updating the IT09 GLF model with respect to high-redshift evolution. We briefly mention the possibility of utilizing such blazars to obtain information on the high-redshift extragalactic background light and early galaxy formation through spectral absorption features.

Throughout this paper, we adopt the standard cosmological parameters of \( (h, \Omega_M, \Omega_\Lambda) = (0.7, 0.3, 0.7) \).

II. THE BLAZAR SED SEQUENCE

Ref. [19, 20, 23] constructed an empirical blazar SED model to describe the SED sequence, based on fittings to observed SEDs from radio to \( \gamma \)-ray bands. These models are comprised of the two components (synchrotron and IC), and each of the two is described by a linear curve at low photon energies and a parabolic curve at high energies.

We construct our own SED sequence model mainly based on the SED model [23], because there is a mathematical discontinuity in the original model of Ref. [28]. Our own SED sequence formula is described in the Appendix of Ref. [20] in detail. In Fig. 1 we show this empirical blazar SED sequence model in comparison with the observed SED data [20, 23].

III. THE MODEL OF GAMMA-RAY LUMINOSITY FUNCTION OF BLAZARS

The cosmological evolution of AGN XLF has been investigated intensively [33–34]. These studies revealed that AGN XLF is well described by the LDDE model, in which peak redshift of density evolution increases with AGN luminosity. Here we construct blazar GLF models based on the two XLFs derived by Ref. [33] (hereafter U03; in hard X-ray band) and Ref. [34] (hereafter H05; in soft X-ray band). The use of LDDE in blazar GLF has been supported from the EGRET blazar data [6].

We simply assume that the bolometric luminosity of radiation from jet, \( P \), is proportional to disk X-ray luminosity, \( L_X \). We relate these two by the parameter \( q \), as \( P = 10^q L_X \). Here, we define the disk luminosity \( L_X \) to be that in the rest-frame 2–10 and 0.5–2 keV bands for the U03 XLF and the H05 XLF , respectively. Thus, the luminosity at rest 100 MeV, \( L_\gamma \), and \( L_X \) have been related through \( P \).

The blazar GLF \( \rho_\gamma \) is then obtained from the AGN XLF, \( \rho_X \), as \( \rho_\gamma(L_\gamma, z) = \kappa \frac{dL_\gamma}{dL_X} \rho_X(L_X, z) \), where \( \rho_\gamma \) and \( \rho_X \) are the comoving number densities per unit gamma-ray and X-ray luminosity, respectively. The parameter \( \kappa \) is a normalization factor, representing the fraction of AGNs observed as blazars. See the §3 in Ref. [28] for a detail.

We use the maximum likelihood method to search for the best-fit model parameters of the blazar GLF.
to the distributions of the observed quantities of the EGRET blazars (gamma-ray flux and redshift). See Ref. [23] for a detail. We take \( q \) and the faint-end slope index of XLF, \( \gamma_1 \) in addition to \( q \) as free parameters. These are hereafter called as U03(\( q \)), H05(\( q \)), U03(\( q, \gamma_1 \)) and H05(\( q, \gamma_1 \)) fits, respectively. Figure 2 shows the distributions of redshift and gamma-ray luminosity predicted by the best-fit models, in comparison with the EGRET data.

We performed the Kolmogorov-Smirnov (KS) test to see the goodness of fits for the best-fit results of each of the four fits, and the chance probabilities of getting the observed KS deviation. Since the best KS test value is obtained for the U03(\( q, \gamma_1 \)) GLF model, we use this GLF model as the baseline below.

IV. THE EGRB SPECTRUM

We calculate the EGRB spectrum by integrating our blazar SED sequence model using the blazar GLF derived in [11]. Since EGRET has already resolved bright gamma-ray sources, we should not include those sources in the EGRB calculation. Therefore, the maximum gamma-ray luminosity in the integration should be \( L_{\gamma}(F_{\text{EGRET}}, z) \), which is the luminosity of the blazar having a flux \( F_{\gamma} = F_{\text{EGRET}} \) at a given \( z \), where \( F_{\text{EGRET}} = 7 \times 10^{-8} \text{ photons cm}^{-2} \text{ s}^{-1} \) is the EGRET sensitivity above 100 MeV.

High energy photons (\( \geq 20 \text{ GeV} \)) from high redshift are absorbed by the interaction with the cosmic infrared background (CIB) radiation [37–40]. We adopt the model of Ref. [38] for the CIB optical depth. We also take into account the cascading emission to calculate EGRB spectrum, considering only the first generation of created pairs [17]. We found that the amount of energy flux absorbed and reprocessed in intergalactic medium is only a small fraction of the total EGRB energy flux, and hence the model dependence of CIB or the treatment of the cascading component does not have serious effects on our conclusions in this work [26].

In addition to blazars, we take into account non-blazar AGNs as the source of EGRB. Ref. [28] (hereafter ITU08) has shown that non-blazar AGNs are a promising source of EGRB at \( \sim 1–10 \text{ MeV} \). In this scenario, a nonthermal power-law component extends from hard X-ray to \( \sim 10 \text{ MeV} \) band in AGN spectra, because of nonthermal electrons that is assumed to exist in hot corona around AGN accretion disks. The existence of such nonthermal electrons is theoretically reasonable, because magnetic reconnection is the promising candidate for the heating source of the hot corona [46] where hard X-ray photons are emitted. Magnetic reconnections should produce nonthermal particles, as is well known in e.g., solar flares or the earth magnetosphere. Although several sources have been proposed as the origin of the MeV background, this model gives the most natural explanation for the observed MeV background spectrum that is a simple power-law smoothly connected to CXB.

Theoretically, there is no particular reason to expect a cut-off of the nonthermal emission around 10 MeV, and it is well possible that this emission extends beyond 10 MeV with the same power index. Then, this component could make some contribution to GeV EGRB. The EGRB spectra from the non-blazar AGNs are calculated based on the model of ITU08. The model parameters of ITU08 have been determined to explain the EGRB in the MeV band. There is some discrepancy between the MeV EGRB data of SMM [43] and COMPTEL [44], and the reason for this is not clear. Here we use two model parameter sets of \( (\Gamma, \gamma_{tr}) = (3.5, 4.4) \) and \( (3.8, 4.4) \) in ITU08, where \( \Gamma \) is the power-law index of nonthermal electron energy distribution and \( \gamma_{tr} \) is the transition electron Lorentz factor above which the nonthermal component becomes dominant. These two parameter sets are chosen so that they fit to the COMPTEL and SMM data, respectively.

A. On the Origin of the EGRB: Comparison with the Fermi EGRB Spectrum

Fig. 3 compares our model predictions with the observed EGRB data, including the very recent Fermi results [4, 54]. Since the flux thresholds of EGRET and Fermi are different, we must be careful when directly comparing with the Fermi data. However, when the sensitivity threshold of Fermi is set to be the same as that of EGRET, the EGRB flux changes by only \( \sim 10 \% \) [47]. Therefore, our predicted EGRB spectrum can be considered to be in excellent agreement with the Fermi data. This agreement strongly suggests that blazars are the principal sources of the EGRB above 1 GeV, and the contribution from other sources like dark matter annihilation is minor. This also implies that use of the blazar sequence is a valid assumption.

The EGRB prediction using the ITU08 non-blazar background model with \( \Gamma = 3.5 \) also agrees nicely with the observed data from X-rays to 100 GeV. In this case, the predicted EGRB flux above 100 MeV can account for 80\% of the observed flux, considerably higher than in previous studies [5, 12, 13]. It should be noted that the contribution to the EGRB flux above 100 MeV from blazars alone is \( \sim 45 \% \), while the remaining \( \sim 35 \% \) comes from non-blazar AGNs.

Based on these results and considerations, we conclude that most, and probably all, of the EGRB flux can be explained by blazars together with non-blazar AGNs, whose luminosity functions are consistent with the EGRET blazar data and X-ray AGN surveys.
FIG. 2: Redshift and gamma-ray luminosity ($\nu L_\nu$ at 100 MeV) distributions of EGRET blazars. The histogram is the binned EGRET data, with one sigma Poisson errors. The four model curves are the best-fits for the GLF models of U03($q$, $\gamma$), H05($q$, $\gamma$), and H05($q$, $\gamma$), as indicated in the figure. Bottom panels: the same as the top panels, but for cumulative distributions.

Recently, based on observations of Swift/BAT-selected blazars at 15–55 keV, Ref. [29] suggested that MeV blazars contribute significantly to the MeV background. However, this conclusion is based on an extrapolation of blazar SEDs from 55 keV to the MeV band, and some fine tuning may be required in the MeV blazar SED to reproduce the EGRB spectrum that connects smoothly with the CXB. Moreover, the spectral break in the EGRB around 10 MeV implies that such MeV blazars are a distinct population from those contributing to the EGRB above 10 MeV. Therefore, it seems more natural that the dominant contribution to the MeV background is coming from non-blazar AGNs as proposed by [28]. Further observational studies are desired to reveal the true origin of the MeV background.

V. PREDICTIONS FOR THE FERMI MISSION

A. Expected Number of Blazars and Non-blazar AGNs

The left panel of Figure 4 shows the cumulative distribution of > 100 MeV photon flux of blazars, non-blazar AGNs, and the total of the two. The GLF predicts that about 750 and 1200 blazars should be selected blazars at 15–55 keV, Ref. [29] suggested that MeV blazars contribute significantly to the MeV background. However, this conclusion is based on an extrapolation of blazar SEDs from 55 keV to the MeV band, and some fine tuning may be required in the MeV blazar SED to reproduce the EGRB spectrum that connects smoothly with the CXB. Moreover, the spectral break in the EGRB around 10 MeV implies that such MeV blazars are a distinct population from those contributing to the EGRB above 10 MeV. Therefore, it seems more natural that the dominant contribution to the MeV background is coming from non-blazar AGNs as proposed by [28]. Further observational studies are desired to reveal the true origin of the MeV background.

B. Non-blazar AGNs and Blazars

As can be seen in Fig. 3 the spectrum of the cosmic MeV background connects smoothly with that of the cosmic X-ray background (CXB), while the spectral index of the EGRB changes abruptly around $\sim$10 MeV. This indicates that the sources of the EGRB below 10 MeV is the same population as that of the CXB (i.e. non-blazar AGNs), and the sources of the EGRB above 10 MeV is a different population (i.e. blazars).
by Fermi with 5-year survey, by their soft nonthermal emission from nonthermal electrons in coronae of accretion disks, giving an interesting test for our model. We estimated the > 100 MeV gamma-ray flux from the observed hard X-ray flux of NGC 4151 (the brightest Seyfert galaxy in all sky [35]) using the ITU08 model [26]. Then, NGC 4151 is marginally detectable when $\Gamma = 3.8$, and easily detectable with $\Gamma = 3.5$ with one year survey sensitivity.

The right panel of Figure 4 shows the differential flux distribution of gamma-ray blazars and non-blazar AGNs multiplied by flux, showing the contribution to the EGRB per unit logarithmic flux interval. EGRB from blazars should practically be resolved into discrete sources. We find that the fraction of EGRB flux that should be resolved is 98% against the total blazar EGRB flux in 5-year survey. On the other hand, EGRB from non-blazar AGNs is hardly resolved into discrete sources by Fermi. The predicted fraction of non-blazar EGRB flux resolved by Fermi is $\sim 0.01$% with 5-year survey, respectively, against the total non-blazar EGRB flux. These results are in sharp contrast to those for blazars, although the contributions to the total EGRB by the two populations are comparable at around 100 MeV.

The above results mean that a considerable part of EGRB at around 100 MeV will remain unresolved even with the Fermi sensitivity, because there is a considerable contribution from non-blazar AGNs to EGRB at $\sim 100$ MeV. However, the contribution from non-blazars should rapidly decrease with increasing photon energy, and almost all of the total EGRB flux at $\gtrsim 1$ GeV should be resolved into discrete blazars by Fermi, if there is no significant source contributing to EGRB other than blazars. It should be noted that these predictions can be tested by Fermi relatively easily, without follow-up or cross check at other wavebands, once measurements of source counts and EGRB flux have been done by the Fermi data. Therefore this gives a simple and clear test for our theoretical model [26].

B. High Redshift Fermi Blazars

Since Fermi is the most sensitive GeV gamma-ray observatory to date, it has the potential to discover many new high-redshift blazars. GeV photons from high-redshift sources are expected to suffer intergalactic absorption due to $e^\pm$ pair production interactions with the cosmic UV background radiation. The resulting features in the spectra of such blazars could therefore be a key probe of the poorly-understood UV background radiation and provide valuable insight into the cosmic dark ages [50, 52].
The high-redshift evolution of the GLF is uncertain, as there are no appropriate samples of gamma-ray blazars and X-ray AGNs above \( z \approx 3 \). Thus we constructed new GLFs by combining the U03 XLF with evolutionary constraints from the Sloan Digital Sky Survey (SDSS) quasar luminosity function data \cite{53}. The SDSS quasar luminosity function is well constrained up to \( z \approx 5 \).

Fig. 5 shows the expected cumulative redshift distribution of blazars that are detectable by Fermi above 100 MeV. Two sets of curves are plotted corresponding to the one- and five-year survey sensitivity. Solid and dashed curves refer to the cases of whether or not the SDSS quasar constraint is taken into account. Note that intergalactic absorption effects are not included here, as they are not expected to be important below 1 GeV \cite{50–52}. The results imply that Fermi may detect some blazars up to \( z \approx 6 \) during the five-year survey. Measurements of the spectra of such blazars above 1 GeV through subsequent, deep observations should provide interesting constraints on the high-z UV background. More details will be presented in a forthcoming publication.

VI. CONCLUSIONS

We have compared our prediction of the EGRB spectrum \cite{20} with the recent Fermi data, and made quantitative predictions for the next four years of the Fermi mission. In Ref. \cite{20}, we constructed a model of the blazar gamma-ray luminosity function (GLF), taking into account the blazar SED sequence and the LDDE luminosity function inferred from X-ray observations of AGNs. The GLF model parameters are constrained by fitting to the observed flux and redshift distribution of the EGRET blazars. With this model, we can predict the EGRB spectrum in a non-trivial way, rather than assuming simple power-law spectra.

The contribution from non-blazar AGNs to the EGRB is also considered, using the nonthermal coronal electron model \cite{28}. This model gives a natural explanation for the observed cosmic MeV background, and we examined whether the X-ray to GeV gamma-ray background radiation can be accounted for by the two population model including blazars and non-blazar AGNs.

Our predicted blazar EGRB spectrum matched very well with the latest Fermi EGRB data. This indicates that blazars are the dominant population of the EGRB and that other components such as dark matter annihilation do not contribute to EGRB significantly. This also indicates that the use of blazar SED sequence was valid. The predicted spectrum including blazars and non-blazar AGNs is also in good agreement with the observed data from X-ray to 100 GeV. Therefore, blazars and non-blazar AGNs are likely the primary sources of the cosmic X-ray and gamma-ray background radiation. Our model predicts that it is possible to account for 80% of the observed EGRB flux above 100 MeV with the sum of the blazar and non-blazar AGN components, where blazars alone account for about 45%. The two components are comparable at \( \sim 100 \text{ MeV} \), with blazars and non-blazar AGNs dominating at higher and lower energies, respectively.

From the viewpoint of the EGRB spectrum from MeV to GeV, we argue that the dominant component contributing to the MeV background is non-blazar AGNs that are also responsible also for the CXB, rather than MeV blazars as proposed by Ref. \cite{29}.

We predicted the flux distribution of blazars by our model, and we found that 750 and 1200 blazars in all sky should be detected by Fermi, assuming a sensitivity limit of \( F_{\text{lim}} = 3 \times 10^{-9} \) and \( 1 \times 10^{-9} \) photons cm\(^{-2}\) s\(^{-1}\) above 100 MeV corresponding to one and five year survey sensitivity. This number is significantly lower than the predictions by many of the previous studies. About 4–50 of non-blazar AGNs are expected to be detected by Fermi with 5-year survey. Fermi should resolve almost all of the EGRB flux from blazars into discrete blazars, with percentages of \( \sim 98\% \) with 5-year survey. On the other hand, less than 0.1% of the EGRB flux from non-blazar AGNs can be resolved into discrete sources. Therefore, we have a clear prediction: Fermi will resolve almost all of the EGRB flux into discrete sources at photon energies \( \gtrsim 1 \text{ GeV} \) where blazars are dominant, while a significant fraction of the EGRB flux will remain unresolved in the low energy band of \( \lesssim 100 \text{ MeV} \) where non-blazar AGNs have a significant contribution. This prediction can easily be tested, only with the source counts and the EGRB estimates by Fermi data.

We also made predictions for future detections of high-redshift blazars. Since the GLF is uncertain at \( z \geq 3 \) due to lack of direct observational data, we constrained the redshift evolution of our original AGN XLF using SDSS quasar data. With this assumption, we find that Fermi may find some blazars up to \( z \approx 6 \) during the five year survey. Such high-redshift GeV blazars will offer a new probe of the formation histories of early stars and galaxies via GeV spectral attenuation signatures caused by the high-redshift UV background radiation.

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