A NEW METHOD TO STUDY THE ORIGIN OF THE EXTRAGALACTIC GAMMA-RAY BACKGROUND AND THE FIRST APPLICATION ON AT20G

Ming Zhou1,2,3, Jiancheng Wang1,2, and Xiaoyan Gao1,2,3
1 National Astronomical Observatories, Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China; mzhou@ynao.ac.cn
2 Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China
3 Graduate School, Chinese Academy of Sciences, Beijing, China

Received 2010 October 28; accepted 2010 December 23; published 2011 January 12

ABSTRACT

In this Letter, we introduce a new method of image stacking to directly study the undetected but possible γ-ray point sources. Applying the method to the Australia Telescope 20 GHz Survey sources which have not been detected by Large Area Telescope on the Fermi Gamma-ray Space Telescope, we find that the sources contribute (10.5 ± 1.1)% and (4.3 ± 0.9)% of the extragalactic gamma-ray background (EGB) and have a very soft spectrum with the photon indices of 3.09 ± 0.23 and 2.61 ± 0.26 in the 1–3 GeV and 3–300 GeV energy ranges, respectively. In the 0.1–1 GeV range, they probably contribute a larger fraction to the EGB, but it is not quite certain. It may not be appropriate to assume that the undetected sources have similar properties to the detected sources.

Key words: gamma rays: diffuse background – methods: statistical – quasars: general

Online-only material: color figures

1. INTRODUCTION

The extragalactic gamma-ray background (EGB) was first detected by the SAS 2 mission (Fichtel et al. 1975), and its spectrum was measured with good accuracy by Fermi (also called isotropic diffuse background; Abdo et al. 2010d). It has been found to be consistent with a featureless power law with a photon index of ∼2.4 in the 0.2–100 GeV energy range and an integrated flux (E > 100 MeV) of 1.03 × 10−5 photons cm−2 s−1 sr−1.

The origin of the EGB is one of the fundamental unsolved problems in astrophysics, and it has been a subject of study for a long time (see Kneiske 2008 for a review). The EGB could originate from either truly diffuse processes or from unresolved point sources. Truly diffuse emission can arise from numerous processes such as the annihilation of dark matter (Ahn et al. 2010), particle acceleration by intergalactic shocks produced during large-scale structure formation (Gabici & Blasi 2003), etc.

Blazars (including BL Lac objects, flat-spectrum radio quasars, or unidentified flat-spectrum radio sources) represent the most numerous population detected by the Energetic Gamma-Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory (Hartman et al. 1999) and by Fermi (Abdo et al. 2010a). Therefore, the blazars that have not been detected by the EGRET or Large Area Telescope (LAT) are the most likely candidates for the origin of the bulk of the EGB emission. Many authors have studied the luminosity function of blazars and showed that the contribution of blazars to the EGRET EGB could be in the range from 20% to 100% (Stecker & Salamon 1996; Naruoto & Totani 2006; Dermer 2007; Cao & Bai 2008; Kneiske & Mannheim 2008; Inoue & Totani 2009).

Nevertheless, starburst galaxy and non-blazar radio-loud active galactic nuclei (AGNs) can also contribute a fairly large fraction of the EGB (Thompson et al. 2007; Bhattacharya & Sreekumar 2009; Bhattacharya et al. 2009).

Recently, Abdo et al. (2010b) built a source count distribution at GeV energy and yielded that point sources that had not been detected by the LAT can contribute 23% of the EGB. At the fluxes currently reached by the LAT, they ruled out the hypothesis that point-like sources (i.e., blazars) produce a large fraction of the EGB.

However, if the properties of undetected sources are not similar to the detected sources, these conclusions maybe not correct. Therefore, we apply an image stacking method to directly study the undetected point sources. For a sample of possible γ-ray point sources that have not been detected by the Fermi due to their faint fluxes or soft spectra (Abdo et al. 2010c), we can stack a large number of them to improve the statistics (Ando & Kusenko 2010). If their fluxes are not too faint, we can derive their mean flux and photon index by a maximum likelihood (ML) method.

2. SAMPLE

The Australia Telescope 20 GHz Survey (AT20G4; Murphy et al. 2010) is the largest catalog of high-frequency radio sources and contains 5890 sources with the flux at 20 GHz exceeding 40 mJy in the whole sky south of declination 0◦. In the south sky, about 60% (230 sources) of AT20G sources are associated with the LAT AGN Catalogue (1LAC) sources are associated with the AT20G sources (Ghirlanda et al. 2010a). Through studying the correlation between the γ-ray and radio flux density of AT20G sources, Ghirlanda et al. (2010b) yielded that AT20G sources not detected by the LAT can contribute 17% of the EGB. Therefore, we apply our methods to study them first.

We exclude the sources identified as Galactic H II regions, Galactic Planetary Nebulae, and parts of the Magellanic Clouds in AT20G, then the majority of sources (5808) we obtain are quasi-stellar objects (see Murphy et al. 2010, but the optical properties of these objects have not been published). In order to minimize the influence of strong sources, we only use the sources that are at least 2′ away from the nearest First Fermi-LAT catalog (1FGL) source and locate at high Galactic latitudes, |b| > 15◦. Finally, we obtain 2900 sources to analyze their contribution to the EGB.

4 It is available online through Vizier (http://vizier.u-strasbg.fr).
3. METHOD

The photons\(^5\) used in our analysis are same as those used by Abdo et al. (2010c) to construct the 1FGL, but ours in the 1–300 GeV energy range have small 68% containment radius (better than 1\(^\circ\)) and little source confusion (see Atwood et al. 2009; Abdo et al. 2009). In this procedure, the tools of gtselect and gtminuit\(^6\) are used.

For stacking the images of all sources, we collect all photons that are at most 1\(^\circ\) away from any source of our sample and then record their energies (\(E_i\), in units of GeV) and angular distances (\(\theta_i\), in units of deg) between the photon and the source. The overlapping of sources has little influence on our method because these sources are very faint and can be regarded as parts of a diffuse background source, especially in the stacked image.

After that, we apply an ML method to derive the flux and photon index of the stacked point source. For simplicity, in our model there are only two sources, e.g., the diffuse background source and stacked point source. We assume that they all have power-law spectra, and the photon indices are \(\gamma_1\) and \(\gamma_2\), respectively. The fluxes density are \(f_1\) (in units of photons cm\(^{-2}\) s\(^{-1}\) GeV\(^{-1}\) deg\(^{-2}\)) and \(f_2\) (in units of photons cm\(^{-2}\) s\(^{-1}\) GeV\(^{-1}\)), respectively. The emission can be expressed by

\[
\frac{dN}{2\pi\theta d\theta dE} = f_1\left(\frac{E}{1\text{ GeV}}\right)^{-\gamma_1} + f_2\left(\frac{E}{1\text{ GeV}}\right)^{-\gamma_2}\times\text{PSF}(\theta, E),
\]

where \(dN(\theta, E)\) is the photon number in the ranges of (\(\theta - \theta + d\theta\)) and (\(E - E + dE\)), PSF is the point-spread function (in the units of deg\(^{-2}\)), exposure is the integral of effective area over time (in units of cm\(^2\) s). PSF and exposure are derived from the tool of gtpsf. The emission must meet the relationship of

\[
\int_0^1 \int_{E_1}^{E_2} [f_1\left(\frac{E}{1\text{ GeV}}\right)^{-\gamma_1} + f_2\left(\frac{E}{1\text{ GeV}}\right)^{-\gamma_2}\times\text{PSF}(\theta, E)]\times\text{exposure}(E)2\pi\theta d\theta dE = N_0.
\]

where \(N_0\) is the total number of photons in the \(E_1\)–\(E_2\) energy range. Therefore, there are only three free parameters. In the practical calculation, we use \(\gamma_1\), \(\gamma_2\), and \(M\). \(M\) is the number of photons contributed by the stacked source. Then \(f_1\) and \(f_2\) can be described by \(\gamma_1\), \(\gamma_2\), and \(M\).

The probability for a photon with \((\theta_i, E_i)\) is

\[
P_i = \frac{\text{exposure}(E_i)2\pi\theta_i}{N_0}\left[f_1\left(\frac{E_i}{1\text{ GeV}}\right)^{-\gamma_1} + f_2\left(\frac{E_i}{1\text{ GeV}}\right)^{-\gamma_2}\times\text{PSF}(\theta_i, E_i)\right].
\]

The likelihood is the probability of the observed data for a specific model. For our case, it is defined as

\[
L = \prod_{i=1}^{N_0} P_i.
\]

The logarithm of the likelihood is much conveniently calculated:

\[
\ln L = \sum_{i=1}^{N_0} \ln \left[ f_1\left(\frac{E_i}{1\text{ GeV}}\right)^{-\gamma_1} + f_2\left(\frac{E_i}{1\text{ GeV}}\right)^{-\gamma_2}\times\text{PSF}(\theta_i, E_i)\right] + \sum_{i=1}^{N_0} \ln \frac{\text{exposure}(E_i)2\pi\theta_i}{N_0}.
\]

Because the last term is model independent, it is not useful for the ML method. Neglecting the last term, we get

\[
\ln L = \sum_{i=1}^{N_0} \ln \left[ f_1\left(\frac{E_i}{1\text{ GeV}}\right)^{-\gamma_1} + f_2\left(\frac{E_i}{1\text{ GeV}}\right)^{-\gamma_2}\times\text{PSF}(\theta_i, E_i)\right].
\]

We maximize numerically \(L\) to obtain the most probable parameters \((f_1, f_2, \gamma_1, \gamma_2)\) of these sources.

We use the likelihood ratio to test the hypothesis. The point-source “test statistic” (TS) is defined as

\[
TS = -2(\ln L_0 - \ln L_1),
\]

where \(L_0\) and \(L_1\) are the likelihood without and with point source. The detected significance of a point source is approximately \(\sqrt{TS} \sigma\) (see Mattox et al. 1996).

4. RESULT AND DISCUSSION

The stacked source is estimated to have a photon index of 2.81 and integrated flux of \(1.07 \times 10^{-7}\) photons cm\(^{-2}\) s\(^{-1}\). The TS is 129, corresponding to a significance of \(\sim 11\sigma\). The mean flux of these sources is \(3.69 \times 10^{-11}\) photons cm\(^{-2}\) s\(^{-1}\); it is fainter than the faintest 1FGL source by a factor of 10. It can contribute 8.4% of the EGB in the 1–300 GeV energy range. We also apply our method to a subsample of flat-spectrum radio sources (i.e., \(\alpha_{20\text{ GHz}} < 0.5\), with \(F_\nu \propto \nu^{-\alpha}\), 1780 sources). Its photon index is 2.79, only slightly harder than the former. Its mean flux is \(3.79 \times 10^{-10}\) photons cm\(^{-2}\) s\(^{-1}\) and the TS is 88. This subsample has not distinct characteristic from the other sources in the \(\gamma\)-ray energy range.

In order to test a more complicated spectral shape of the stacked source, we analyze the spectrum in the 1–10 GeV energy range. We expect that the spectrum would be harder in this energy range. However, the estimated photon index is 3.01. Therefore, we analyze the spectrum in the 2–10 GeV and 3–10 GeV energy ranges, respectively. The results are summarized in Table 1. We find that the spectrum is very soft in the 1–3 GeV energy range and becomes harder above 3 GeV. It is indicated that two types of sources exist, in which one is with softer and another is with harder spectrum in the GeV range. The former will dominate in lower energies and latter in higher energies. Therefore, the spectrum of the stacked source shows very soft in the 1–3 GeV energy range. We will study this further if the optical properties of these objects can be obtained.

Finally, we obtain the properties of the spectrum as follows. In the 1–3 GeV, the photon index is 3.12, the mean integrated flux is \(3.89 \times 10^{-10}\) photons cm\(^{-2}\) s\(^{-1}\), and the TS is 92. Obviously, the flux is larger than that in the 1–300 GeV energy range. It could be caused by the fact that the spectrum in the 1–300 GeV is not well fitted with a single power law. In the 3–300 GeV, the photon index is 2.66, the mean integrated flux is \(3.72 \times 10^{-12}\) photons cm\(^{-2}\) s\(^{-1}\), and the TS is 38.

A decrease in \(\ln L\) of 0.5 from its maximum value corresponds to the 68% confidence (1\(\sigma\) region for each parameter (see Mattox et al. 1996). We use this variance to estimate the error of each parameter. In three parameters \((\gamma_1, \gamma_2, \text{ and } M)\), we take two

\(^5\) http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

\(^6\) These and other tools we used in next are accessible at http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html.
The Astrophysical Journal Letters, 727:L46 (4pp), 2011 February 1

Figure 1. Change of likelihood from its maximum with $\gamma_2$ (top) or $M$ (bottom) around their best value when other parameters are fixed on their highest likelihood value. Right and left panels are for the 1–3 GeV and 3–300 GeV bands, respectively.

(A color version of this figure is available in the online journal.)

The results in different energy ranges are shown in Figure 2. They are compatible with Gaussian distributions. In the 1–3 GeV and 3–300 GeV, the mean fluxes are 3.48 ± 0.36 and 0.380 ± 0.080 (in the unit of $10^{-11}$ photons cm$^{-2}$ s$^{-1}$), their relative errors are 10.3% and 20.7%, and the photon indices are 3.09 ± 0.23 and 2.61 ± 0.26, respectively, while the contributions to the EGB are (10.5 ± 1.1)% and (4.3 ± 0.9)% respectively, which are much smaller than the result (17%) of Ghirlanda et al. (2010b). If the soft spectrum in 1–3 GeV is caused by the spectral broken of some sources, the photon index would not be extrapolated to lower energy range. However, as long as the spectrum of stacked source is not harder than the EGB, the contribution to the EGB in 0.1–1 GeV will be larger than that in 1–3 GeV. Our result is compatible with the result (23%) of Abdo et al. (2010b) because other point sources could contribute to the EGB.

In this Letter, we introduce a new method of images stacking to directly study the contribution of undetected point sources to the EGB. Our method is more direct than the methods used...
Figure 2. Distributions of photon indices (top), mean fluxes (middle), and TS (bottom). Right and left panels are for the 1–3 GeV and 3–300 GeV bands, respectively. The distribution can be represented by Gaussian functions (dashed line) with central values $\mu = 3.15 (2.71), 4.30 (0.364) \times 10^{-11}, 110 (37)$, respectively, standard deviations $\sigma = 0.23 (0.26), 4.44 (0.755) \times 10^{-12}, 21 (13)$, in the 1–3 (3–300) GeV. The input photon indices are 3.12, 2.66 and fluxes are 3.87, 0.372 (in unit of $10^{-11}$ photons cm$^{-2}$ s$^{-1}$), respectively, which are indicated by vertical lines.

(A color version of this figure is available in the online journal.)

by many authors. Those methods involve the $\gamma$-ray luminosity of undetected sources which is estimated through the properties of a few detected sources. They include many uncertainties and lead the result to be of questionable validity.

Applying our method, we find that the undetected sources in AT20G can contribute (10.5 $\pm$ 1.1)$\%$ and (4.3 $\pm$ 0.9)$\%$ to the EGB in the 1–3 GeV and 3–300 GeV energy ranges, respectively. Their $\gamma$-ray spectrum is very soft, implying that the emissive property is different for undetected and detected sources.

Applying our method to estimate the contribution of all point sources to the EGB, we need a complete sample of possible $\gamma$-ray point sources, which is not easily constructed. In this Letter, we only estimate the contribution of AT20G to the EGB. We will study more samples of possible $\gamma$-ray point sources in the future.

We thank the LAT team and AT20G team providing the data on the Web site. We acknowledge the financial supports from the National Natural Science Foundation of China 10778702, the National Basic Research Program of China (973 Program 2009CB824800), and the Policy Research Program of Chinese Academy of Sciences (KJCX2-YW-T24).

REFERENCES

Abdo, A. A., et al. 2009, ApJS, 183, 46
Abdo, A. A., et al. 2010a, ApJ, 715, 429
Abdo, A. A., et al. 2010b, ApJ, 720, 435
Abdo, A. A., et al. 2010c, ApJS, 188, 405
Abdo, A. A., et al. 2010d, Phys. Rev. Lett., 104, 101101
Ahn, E. J., Bertone, G., Merritt, D., & Zhang, P. J. 2007, Phys. Rev. D, 76, 023517
Ando, S., & Kusenko, A. 2010, ApJ, 722, L39
Atwood, W. B., et al. 2009, ApJ, 697, 1071
Belikov, A. V., & Hooper, D. 2010, Phys. Rev. D, 81, 043505
Bhattacharya, D., & Sreekumar, P. 2009, Res. Astron. Astrophys., 9, 509
Bhattacharya, D., Sreekumar, P., & Mukherjee, R. 2009, Res. Astron. Astrophys., 9, 1205
Cao, X. W., & Bui, J. M. 2008, ApJ, 673, L131
Cuoco, A., Sellerholm, A., Conrad, J., & Hannestad, S. 2010, MNRAS, submitted (arXiv:1005.0843)
Dermer, C. D. 2007, ApJ, 659, 958
Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Ogelman, H., Ozel, M. E., Turner, T., & Bignami, G. F. 1975, ApJ, 198, 163
Gabici, S., & Blasi, P. 2005, Astropart. Phys., 19, 679
Ghirlanda, G., Ghisellini, G., Tavecchio, F., & Foschini, L. 2010a, MNRAS, 470, 791
Ghirlanda, G., Ghisellini, G., Tavecchio, F., Foschini, L., & Bonnoli, G. 2010b, MNRAS, submitted (arXiv:1007.2751)
Hartman, R. C., et al. 1999, ApJS, 123, 79
Inoue, Y., & Totani, T. 2009, ApJ, 702, 523
Kneiske, T. M. 2008, Chin. J. Astron. Astrophys. Suppl., 8, 219
Kneiske, T. M., & Mannheim, K. 2008, A&A, 479, 41
Mattox, J. R., et al. 1996, ApJ, 461, 396
Murphy, T., et al. 2010, MNRAS, 402, 2403
Narumoto, T., & Totani, T. 2006, ApJ, 643, 81
Stecker, F. W., & Salamon, M. H. 1996, ApJ, 464, 600
Thompson, T. A., Quataert, E., & Waxman, E. 2007, ApJ, 654, 219