GRB observation by Fermi LAT revisited

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Abstract: We search the Fermi-LAT photon database for an extended gamma-ray emission which could be associated with any of the 581 previously detected gamma-ray bursts (GRBs) visible to the Fermi-LAT. For this purpose we compare the number of photons with energies $E > 100$ MeV and $E > 1$ GeV which arrived in the first 1500 seconds after the burst from the same region, to the expected background. We require that the expected number of false detections does not exceed 0.05 for the entire search and find the high-energy emission in 19 bursts, four of which (GRB 081009, GRB 090720B, GRB 100911 and GRB 100728A) were unreported up to date (April 2011). The first three are detected at energies above 100 MeV, while the last one shows a statistically significant signal only above 1 GeV.

Keywords: Fermi LAT, gamma-ray burst, statistical analysis

1 Introduction

Gamma-ray bursts (GRBs) are one of the brightest phenomena in the Universe. Although the majority of GRBs were detected at energies ranging from hundreds of keV to several MeV, they were also observed at much higher energies up to tens of GeV [1]. The advent of the Fermi Large Area Telescope (LAT) with its unprecedented sensitivity [2, 3] has greatly increased our capability to study the high-energy emission from GRBs [4].

The high-energy (HE) emission was detected both in the prompt and afterglow phases of GRBs. However, its origin is still unclear: it could be produced in the internal/external shocks via leptonic or hadronic mechanisms, or in the process of dissipation of the Poynting flux (e.g., [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]). Detailed information on the high-energy γ-ray prompt and afterglow emission could shed light on the onset of GRB and its immediate interaction with surrounding interstellar medium.

GRB observations in the HE band are one of the key science topics of Fermi-LAT. The Fermi Gamma-Ray Burst Monitor (GBM) can initiate autonomous slew of the spacecraft to provide the best conditions for a dedicated GRB observation. Also, knowledge of time and position of a GRB (either provided by GBM or by other observations) makes it feasible to search for GRBs in the LAT photon database where they would manifest themselves as spatially and temporally compact clusters of photons [3]. There has been 20 LAT detections of GRBs as of the time of writing (Feb 2011).

Observations of several very bright bursts (GRB 080916C, GRB 090510, GRB 090902B, GRB 090926A) containing more than 100 photons with energies in excess of 100 MeV allowed one to study the spectral properties of the HE emission and even their temporal evolution [18, 19, 20, 21]. In all these cases the HE emission demonstrated a delay (of several seconds for long bursts, tenth of a second for the short burst GRB 090510) with respect to the prompt emission in the sub-MeV energy range. The HE emission also lasted much longer. The observations indicated a significant deviation from the so-called 'Band function' [22], namely, the presence of a hard power-law component that dominates at high energies (e.g., [19]). Observations of the short GRB 090510 [20] were especially fruitful: first, they proved the intrinsic similarity of the HE emission between short and long bursts; second, the detection of a photon with energy over 30 GeV made it possible to evaluate the Lorentz factor of the jet $\Gamma \sim 1000$; finally, the simultaneous detection of signals in different energy ranges of GBM and LAT allowed one to put constraints on some quantum gravity theories which predict Lorentz invariance violation and energy-dependent speed of light [23, 24].

In this talk we use the Fermi-LAT data to search for a high-energy emission related to GRBs. A similar question was addressed in a number of recent papers. In the papers by [25, 26] the matched filtering technique was implemented and three detections of HE emission were claimed. In the paper by [27] the HE fluence associated with several bright GBM events was constrained.

Unlike the above studies, we looked for a HE emission that could extend over longer time spans than were examined previously and which therefore could have been missed. For this purpose we searched the LAT database for HE photons in two energy bands ($E > 100$ MeV and $E > 1$ GeV) and selected those which came from the directions of 581 previously detected GRBs within the time window of 1500 s either before or after the burst. We then estimated the statistical significance of the excess by comparing the observed number of photons with the expected background, taking into account the penalty for the total number of trials. The detection criterion was chosen in such a way that the entire search would give a single false detection with the probability of 0.05. We found 4 previously unreported GRBs showing the post-burst HE emission, and none showing the pre-burst emission.

2 Data

The LAT detector has a sensitivity to photons with energy above 30 MeV with a wide field of view (FOV) of ~ 2.4 sr and the effective area of up to 9500 cm^2. The detector angular resolution is a function of the incident photon energy and the 'event class' which is determined by the set of reconstruction cuts [28]. It also depends on the angle between the instrument axis and the arrival direction of a photon, but as we do not have explicit knowledge of this dependence, we use the mission-average value. An extensive review of the instrumental capabilities can be found in [2]. In this talk we use the LAT weekly all-sky data that are publicly available at Fermi mission website[1]. The analysis covers the time period of 127 weeks from August 04, 2008 to January 07, 2011, corresponding to mission elapsed time (MET) from 239557417 s to 316111862 s.

We use the 'diffuse' event class and impose an Earth relative zenith angle cut of $105°$. We discard the photons from 'transient' and 'source' classes. The inclusion of these classes would decrease the signal-to-background ratio which becomes an important factor for our comparatively long time window (see [26] for detailed discussion of event classes with respect to GRBs). We do not require the rocking angle cut of $52°$ in order to keep photons observed in the pointing mode, including repoint requests caused by the GRB trigger.

For the spatial selection of photons we adopt the 95% containment angle $\alpha_{95}(E, v)$ corresponding to the point spread function (PSF) for the "diffuse' class photons [28, 29, 30]. This angle depends on both the photon energy and the conversion type v. The latter takes two discrete values: 0 and 1 for front and back converted photons, respectively.

In our analysis we used the times and coordinates of the GRBs detected by other instruments such as GBM[2] [31], Swift[3] [32], INTEGRAL[4] [33], MAXI [34] and Konus-Wind [35]. We have compiled two non-overlapping list of GRBs. The first list included 605 GRBs detected by Fermi GBM and the second 279 GRBs detected by other instruments only. Of these, 444 and 137 GRBs, respectively, were in the Fermi-LAT FOV at least for some part of 1500 s after the burst. Note that although we used time stamps from the original observations, localizations in many cases were provided by much more precise follow-up observations; these data were obtained through the Gamma-ray bursts Coordinates Network (GCN; http://gcn.gsfc.nasa.gov/).

3 Method

The key quantity in our analysis is the probability p that the observed HE emission from the direction of a given GRB is a fluctuation of the background. If this probability is smaller than the certain threshold, we claim the detection of the high energy emission from that burst. The significance threshold is obtained by requiring that the number of false detections does not exceed 0.05 in the entire set. Taking into account that the total number of bursts is 581 and counting two energy ranges as independent, one obtains the following condition:

$$p \; < \; 5 \cdot 10^{-5} \tag{1}$$

for either of the two energy regions.

The probability p for a given burst and given energy threshold E_0 is calculated as follows. Let t_b, l_b and b_b be the trigger time and galactic coordinates of a GRB. First, we determine the observed number of photons n above the energy E_0 by counting photons satisfying the following conditions:

$$\begin{gathered} E > E_0\,, \\ \alpha(l, b, l_b, b_b) < \sqrt{\alpha_{95}^2(E, v) + \alpha_{\rm GRB}^2}\,, \\ t_b \le t \le t_b + 1500\,{\rm s}\,, \end{gathered} \tag{2}$$

where t, l, b, E and v stand for arrival time, coordinates, energy and conversion type of a photon, $\alpha(l, b, l_b, b_b)$ is the angular separation between photon and GRB, and $\alpha_{\rm GRB}$ is the GRB pointing error. The energy threshold E_0 is either 100 MeV or 1 GeV. These conditions select photons with energies larger than E_0 that arrived within 1500 s after the burst from the region of interest (ROI). The latter is a circle with the energy-dependent radius determined by the two contributions: the error of the photon arrival direction and the error of the GRB position. Usually the first contribution dominates. The error of the GRB position was taken to be equal to $1°$ in the case of GBM bursts and $0.5°$ in the case of bursts detected by Swift. Errors for all other bursts were

1. http://fermi.gsfc.nasa.gov/ssc/data/access/
2. http://fermi.gsfc.nasa.gov/ssc/data/access/
3. http://swift.gsfc.nasa.gov/docs/swift/
4. http://www.isdc.unige.ch/integral/

GRB name	$E > 100$ MeV			$E > 1$ GeV		
	B	n	p	B	n	p
080916C	4.1	125	6.4e-135	0.065	18	6.4e-38
*081009	1.9	11	6.3e-6	0.032	1	0.031
081024B	0.34	5	3.0e-5	0.0044	1	4.4e-3
090217A	0.83	10	2.0e-8	0.0090	1	9.0e-3
090323	1.3	31	1.3e-31	0.012	4	9.2e-10
090328	3.7	28	6.0e-16	0.043	8	2.6e-16
090510	3.0	121	2.0e-144	0.036	27	1.3e-67
090626	1.1	10	3.3e-7	0.020	0	1.0
*090720B	4.3	16	1.2e-5	0.070	0	1.0
090902B	2.8	166	2.9e-226	0.036	33	2.1e-85
090926A	0.43	130	3.1e-268	0.0051	20	6.7e-65
091003A	4.1	25	2.7e-12	0.034	3	6.1e-6
091031	2.8	13	6.7e-06	0.028	1	0.027
100116A	2.2	14	1.2e-7	0.033	4	4.8e-8
100414A	3.1	20	1.7e-10	0.039	4	9.5e-8
100724B	0.45	6	7.6e-6	0.0046	0	1
*100728A	4.4	10	0.015	0.065	4	7.1e-7
*100911	0.060	3	3.4e-5	0.0002	0	1
101014A	1.04	8	1.4e-5	0.0048	0	1

Table 1: List of Fermi-LAT GRBs showing extended high-energy emission. B is the expected background, n is the observed number of photons, and p is the probability that the signal is fluctuation of the background. Previously unreported candidates are marked with the star.

determined individually from the GCN website. The observed pre-burst photons are selected by an obvious modification of the conditions (2).

Next, we calculate the expected background B corresponding to the energy $E > E_0$. Since GRBs are exceptional events, for the background calculation we may use the photons from the same spatial region for the entire duration of the mission. Thus, the background is given by the total number of photons observed from the ROI during the whole mission, multiplied by the ratio of the exposure corresponding to 1500 s after the burst to the total exposure of ROI.

Finally, having calculated the observed number of photons n and the expected background B, the probability p for the GRB in question is calculated from the Poisson distribution,

$$p = \mathcal{P}(B, n),$$

where $\mathcal{P}(B, n)$ is the probability to observe n or more events at B expected. If this probability satisfies the condition (1) for at least one of the two energy regions of interest, we have a detection and include the corresponding GRB in the detection list, Table 1.

4 Results and conclusions

Applying the method of Sect. 3 to 581 GRB we have achieved 19 detections of the post-burst HE emission, of which 4 (namely, GRB 081009, GRB 090720B, GRB 100728A and GRB 100911) were unreported up to date (April 2011). All detections correspond to GRBs present in the Fermi-GBM part of the GRB list. No pre-burst HE emission was found. Of the new detections, GRB 100728A demonstrated particularly bright and long HE afterglow: 4 photons with energy > 1 GeV were observed vs. 0.065 expected from the background, the chance probability being $p = 7 \cdot 10^{-7}$. Photon arrival times relative to the burst trigger time are 711.3 s, 713.8 s, 1161.0 s and 1342.5 s. GRB 081009, GRB 090720B and GRB 100911 were observed with the rocking angle less than 52°, while during the GRB 100728A the rocking angle exceeded 52° 1220 s after the burst.

GRB name	$E > 100$ MeV			$E > 1$ GeV		
	B	n	p	B	n	p
080825C	2.3	8	2.8e-3	0.037	0	1
081215	0	0	1	0	0	1
100225A	3.2	4	0.39	0.042	0	1
100325A	2.8	6	0.06	0.026	0	1
100707A	0	0	1	0	0	1

Table 2: List of previously detected Fermi-LAT GRBs missed by our algorithm.

The total number of previously reported GRBs detected by Fermi-LAT is 20. Our algorithm failed in 5 cases; they are listed in Table 2. Two of them (GRB 081215A and GRB 100707A) resided far from the Fermi-LAT axis at approximately 90° angular distance. Their original detections were made with the use of the non-standard analysis technique [36, 37]. Our algorithm is based on the standard event reconstruction and does not treat events outside of LAT FOV.

In our procedure we have treated the background events as a Poissonian process. This approach would fail in case of a moving gamma ray source (the Sun or the Moon) crossing the region of interest just at the moment of burst. We have explicitly checked that no such events happened for the reported candidates. We have also assumed that the background flux is stationary. This could lead to an erroneous detection if some gamma-ray sources in the region of interest flared at the moment of the GRB. This issue should be investigated separately; one can use the LAT 1-year Point Source Catalog [38] for this purpose. No known sources appear within 95% containment radius of all GeV photons attributed to GRB 100728A; the same is valid for GRB 081009. On the contrary, there are numerous sources in the neighborhoods of GRB 090720B and GRB 100911. The question of a possible influence of variability of these sources on the present analysis will be studied elsewhere. Finally, to test for a possible influence of the magnetospheric flares[5] we calculated the gamma-ray flux during 1500 s after the burst in the ring between 15° and 20° from its location, and compared it to the expected background. No indication of magnetospheric flares coincident with the reported new detections was found.

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