Search for GeV Counterparts to Fast Radio Bursts with Fermi

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Abstract

The non-repeating fast radio bursts (FRBs) could arise from catastrophic stellar explosions or magnetar giant flares, so relativistic blast waves might be produced in these events. Motivated by this, we search here for GeV counterparts to all non-repeating FRBs with the Fermi Large Area Telescope (LAT), including FRB 131104 that is claimed to be possibly associated with a γ-ray transient candidate detected by the Swift Burst Alert Telescope. FRB 131104 enters the field of view of LAT ∼ 5000 s after the burst time, so we are only able to search for the GeV afterglow emission during this period, but no significant GeV emission is detected. We also perform a search for GeV emissions from other FRBs, but no significant GeV emissions are detected either. Upper limit fluences in the range of (4.7–29.2) × 10−7 erg cm−2 are obtained, and the upper limits of the isotropic blast-wave kinetic energy of about (1–200) × 1053 erg are inferred under certain assumptions. Although the current limits on the isotropic blast-wave energy are not sufficiently stringent to rule out the connection between FRBs and GRB-like transients, future more sensitive observations with Fermi or Imaging Atmospheric Cherenkov Telescopes might be able to constrain the connection.

Key words: gamma-ray burst: general – gamma rays: general – radiation mechanisms: non-thermal

1. Introduction

Fast radio bursts (FRBs) are intense bursts of radio emission that have durations of milliseconds and have large dispersion measures (DMs). They were first discovered in the archival data from the Parkes telescope, as reported in Lorimer et al. (2007) and Thornton et al. (2013), and subsequently by other radio telescopes as well (Petroff et al. 2015). The origin of these radio bursts is still an enigma, even though more than a dozen FRBs have been found (Petroff et al. 2016).

Their large DMs exceed predictions for the Galaxy, suggesting that the FRBs are extragalactic and possibly cosmological in origin (Thornton et al. 2013; Ravi et al. 2016). The DM contributed by the host galaxy, the possible intervening galaxy, and the plasma around the FRB sources is unknown, so the distances of the FRB sources are uncertain. Recently, owing to the multi-wavelength follow-up observations of the host galaxy of the repeating source FRB 121102 (Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017), the distance scale of this FRB has finally settled to be cosmological (~Gpc). At these distances, the isotropic-equivalent energy output of a typical FRB is about 1038 to 1042 erg. Such energetics, together with the millisecond duration, suggest that FRBs are likely related to compact objects, including non-catastrophic, sometimes repeatable events (e.g., Popov & Postnov 2010; Kulkarni et al. 2014; Loeb et al. 2014; Geng & Huang 2015; Connor et al. 2016; Dai et al. 2016b; Katz 2016; Wang et al. 2016) and catastrophic events such as compact star mergers (e.g., Kashiyma et al. 2013; Totani 2013; Zhang 2014; Mingarelli et al. 2015; Zhang 2016).

Such merger systems are expected to produce relativistic blast waves and in turn to produce multi-wavelength afterglows (Nisino et al. 2014; Yi et al. 2014; Murase et al. 2016). The giant flares of soft γ-ray repeaters (SGRs) also produce blast waves, and thus long-term radio emission, as observed in SGR 1806-20 (Frail et al. 1999; Cameron et al. 2005; Gaensler et al. 2005; Wang et al. 2005). There have been efforts to search for electromagnetic counterparts to FRBs. For example, FRB 150418 was widely searched for at an energy range from radio to very high energy γ-ray (TeV), but it yielded a null result (Akiyama & Johnson 2016; Williams & Berger 2016; H.E.S.S. Collaboration et al. 2017). It was recently reported that a γ-ray transient candidate was coincident with the FRB 131104, with an association significance of about 3.2σ (DeLaunay et al. 2016). The transient is located near the edge of the Burst Alert Telescope’s (BAT) field of view (FoV), leading to a low-significance signal in spite of a relatively bright fluence of $F_S \approx 4 \times 10^{-6}$ erg cm$^{-2}$, which is comparable to that of cosmological γ-ray bursts (GRBs). However, Shannon & Ravi (2017) argue that the association between the γ-ray transient and the FRB is not compelling due to the non-detection of radio afterglow emission at the original location region of the Swift/BAT transient and the discovery of a radio AGN spatially and temporally coincident with FRB 131104. Interestingly, Bannister et al. (2012) searched the radio pulse emission from nine gamma-ray bursts and detected single dispersed pulses following two GRBs at a significance >6σ. A simple population argument supports a GRB origin with confidence of about 2%, and they cannot rule out radio frequency interference as the origin of these pulses.

If the association between FRB 131104 and the Swift/BAT transient is real, this would open up the possibility that FRBs may be accompanied by relativistic shock phenomena similar to GRB afterglows. Multi-wavelength afterglow emission is then expected, but searches for the radio, optical, and X-ray afterglows have been unsuccessful. The intensity of the radio to X-ray afterglow emission depends on the density of the circumburst medium. Using the non-detection, several groups have constrained the density of the medium to be very tenuous, i.e., $n \lesssim 10^{-3}$ cm$^{-3}$ (Dai et al. 2016a; Gao & Zhang 2017; Murase et al. 2017). On the other hand, we note that GeV afterglow emission is independent of the circumburst density,
so searches for GeV afterglow emission using Fermi-Large Area Telescope (LAT) would be useful to test the relativistic shock scenario, independent of the circumburst environment. Furthermore, several GRBs with a fluence comparable to the Swift/BAT transient possibly associated with FRB 131104 have been found to emit prompt or/and afterglow GeV emission. So we also attempt to search for the GeV prompt or/ and afterglow emission associated with FRBs, assuming that FRBs are associated with some type of GRBs.

Yamasaki et al. (2016) have focused on a blind search of millisecond γ-ray flashes over the whole set of 8 year LAT data, without regard to the known FRB triggers, implicitly assuming any GeV counterparts to FRBs are of similar millisecond duration. In contrast to Yamasaki et al. (2016), our current work is to search for any GeV emission counterparts of the reported non-repeating FRBs in the literature, utilizing data taken from the LAT observations on board the Fermi satellite. In Section 2, we describe the Fermi-LAT data analysis. In Section 3, we discuss our data analysis results. The simple summary is given in Section 4.

2. Fermi-LAT Data Analysis

Fermi-LAT, the primary instrument on board the Fermi Gamma-ray Space Telescope, is an imaging, wide FoV (2.4 sr), and high-energy (20 MeV–~300 GeV) detector. For more details about the LAT, the reader is referred to Atwood et al. (2009). The effective area and energy range increase in the latest Pass 8 data. Utilizing the newly released Fermi-LAT Pass 8 data and Fermi Science Tools (v10r0p5) with the P8R2_SOURCE_V6 instrument response functions, we search for GeV prompt or/and afterglow emission of the potential γ-ray transient associated with non-repeating FRBs. We consider all SOURCE class events (i.e., evclass = 128 and etype = 3) in the energies between 100 MeV and 100 GeV within a 10° region of interest (ROI) centered on each FRB position. Furthermore, we use a zenith angle cut of $Z_{\text{max}} < 90°$ to greatly reduce contamination by the Earth limb emission and apply the recommended data-quality cuts of (DATA_QUAL $> 0$) && (LAT_CONFIG $== 1$). The unbinned likelihood analysis is performed with a source model including a point source with a power-law spectrum ($dN/dE = A \times (E/E_0)^{-\gamma}$) on each FRB position, the two diffuse emission components, i.e., Galactic diffuse emission model (gll_iem_v6.fits) and the isotropic diffuse emission model (isop_P8R2_SOURCE_V6_v06.txt), and the 3FGL sources (Acero et al. 2015) within 15° of the ROI center. The time interval for Fermi-LAT analysis is selected when the FRB region enters the FoV of Fermi-LAT after FRB detection time, and the start and stop times are given by the angle $\Theta < 70°$, which is the angular distance between the FRB position and Fermi-LAT boresight. The analysis time interval for each FRB is listed in Table 1. For the analysis of the short time period of a few thousand seconds, the normalization factors of all 3FGL sources is left to vary, and the spectral indices are frozen to their catalog values to solve convergence problems. No significant high-energy γ-ray emission at the FRB positions are found, and thus we get the upper limit fluences at the 95% confidence level with fixed spectral indices of $\Gamma = 2.2$. We have checked our analysis results with the transient data (using the corresponding response function IRFs=P8R2_TRANSIENT020_V6) or different spectral index, and no significant difference is found.

The fluence of the possible γ-ray transient associated with FRB 131104 reached $\sim 10^{-6}$ erg cm$^{-2}$, which is comparable to the prompt fluence of typical GRBs. For comparison, we try to

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### Table 1

Upper Limits of the γ-Ray Fluxes of FRBs Observed by Fermi-LAT

| Name      | $(l, b)^a$  | $T + T_0^b$ | Fluence Limit | $E_{\text{c}}$ Limit | $\text{DM}_{\text{non-Galaxy}}^c$ | $z^d$ |
|-----------|-------------|-------------|---------------|-----------------------|-----------------------------------|------|
| FRB 131104| $(260.5, -21.9)$ | [5417, 11142] | 19.8          | 190.8                 | 707.9                             | 0.59 |
| FRB 090625| $(226.4, -60.0)$ | [0, 595]   | 8.7           | 7.19                  | 867.8                             | 0.72 |
| FRB 110703| $(80.9, -59.0)$ | [0, 1660]  | 16.2          | 16.7                  | 1071.2                            | 0.89 |
| FRB 121002| $(308.2, -26.2)$ | [0, 5119]  | 29.2          | 51.6                  | 1554.9                            | 1.3  |
| FRB 130628| $(225.9, 30.6)$ | [0, 305]   | 16.4          | 3.7                   | 417.3                             | 0.35 |
| FRB 150418| $(232.6, -3.2)$ | [0, 1193]  | 4.7           | 1.9                   | 587.7                             | 0.49 |
| FRB 150807| $(336.7, -54.4)$ | [0, 4946]  | 10.1          | 0.4                   | 196.5                             | 0.16 |
| FRB 110220| $(50.8, -54.7)$ | [2488, 4978] | 7.1           | 99.6                  | 909.6                             | 0.76 |
| FRB 110523| $(56.1, -37.8)$ | [1487, 2687] | 7.4           | 44.2                  | 579.7                             | 0.48 |
| FRB 110626| $(355.8, -41.7)$ | [4622, 6152] | 5.6           | 115.9                 | 675.5                             | 0.56 |
| FRB 120127| $(49.2, -66.2)$ | [1514, 3284] | 13.6          | 50.6                  | 521.4                             | 0.43 |
| FRB 130626| $(7.4, 27.4)$ | [2085, 4305] | 7.3           | 88.8                  | 885.5                             | 0.74 |
| FRB 130729| $(324.7, 54.7)$ | [302, 2842] | 8.7           | 23.5                  | 830                               | 0.69 |
| FRB 140514| $(50.8, -54.6)$ | [1688, 3488] | 7.9           | 34.7                  | 527.8                             | 0.44 |

**Notes.** The first column represents the FRB names. The second column represents the position in the Galactic coordinate system. The third column represents the analysis time intervals relative to the FRB detection times. The fourth column represents the upper limit fluences in $10^{-2}$ erg cm$^{-2}$. The fifth column represents the estimated upper limits of the isotropic blast-wave energy. The last two columns represent the FRB non-Galactic DM and the redshift derived from this non-Galactic DM value, respectively.

* http://www.astronomy.swin.edu.au/pulsar/frbcat/

* The analysis time interval is selected requiring that the angular distance between the FRB position and the Fermi-LAT boresight is $\leq 70°$. $T_0$ refers to each FRB detection time.
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Figure 1. Upper limit fluence of each FRB in 0.1–100 GeV. The red one represents FRB 131104, which is possibly associated with the Swift/BAT transient.

Figure 2. Fermi-LAT fluences vs. Swift/BAT fluences for GRBs detected by both instruments. For comparison, the red data are for FRB 131104, which is possibly associated with the Swift/BAT transient.

Table 2

| Name            | T + T0 (s) | Fluence BAT ($\times 10^{-7}$) (erg cm$^{-2}$) | Fluence LAT ($\times 10^{-7}$) (erg cm$^{-2}$) |
|-----------------|------------|--------------------------------|---------------------------------------------|
| GRB 100728A     | [6, 750]   | 380                            | 49.6 ± 40.4                                 |
| GRB 110625A     | [0, 1000]  | 280 ± 10                       | 133.0 ± 31.2                                |
| GRB 110709A     | [6, 42]    | 100 ± 2                        | 6.2 ± 3.1                                   |
| GRB 110731A     | [3, 24]    | 60 ± 1                         | 45.8 ± 10.3                                 |
| GRB 120624B     | [100, 1300]| 283 ± 4                        | 127.2 ± 19.9                                |
| GRB 120729A     | [400, 800] | 24 ± 1                         | 17.7 ± 8.4                                  |
| GRB 130427A     | [0, 10000]| 3100 ± 30                      | 3070.0 ± 298.0                              |
| GRB 130907A     | [3000, 20000]| 1400 ± 10                      | 163.0 ± 116.5                               |
| GRB 140102A     | [0, 1000]  | 77 ± 2                         | 64.0 ± 41.6                                 |
| GRB 140323A     | [0, 1000]  | 160                            | 25.0 ± 12.9                                 |
| GRB 150314A     | [0, 250]   | 220 ± 3                        | 13.8 ± 5.6                                  |
| GRB 150403A     | [0, 2000]  | 170 ± 3                        | 47.0 ± 32.0                                 |
| GRB 150513A     | [0, 500]   | 54 ± 2                         | 26.8 ± 18.4                                 |
| GRB 160325A     | [0, 2000]  | 71 ± 2                         | 45.6 ± 13.3                                 |
| GRB 160821A     | [0, 175]   | 72 ± 2                         | 57.2 ± 11.3                                 |
| GRB 160905A     | [0, 100]   | 150 ± 2                        | 36.4 ± 22.6                                 |

FRB 131104 [5417, 11142] 40 ± 18 ≤19.8

Notes. The first column is the GRB names. The second column is the Fermi-LAT analysis time intervals. The third column represents the fluences of the prompt emission detected by Swift/BAT. The fourth column represents the fluences in 0.1–100 GeV detected by Fermi-LAT.

interval, with the corresponding P8R2_TRANSIENT020_V6 and P8R2_SOURCE_V6 instrument response functions, respectively. The size of the ROI of each GRB is 12°. We excluded the Earth Limb emission with the zenith angle cut of Z$_{max}$ < 90°.

The upper limit GeV fluences of the point source centered on each FRB position are presented in Table 1 and Figure 1. One can see that no FRB shows any significant GeV emission, which could be used to constrain the energy of relativistic blast waves in some FRB models based on certain assumptions (see Section 3). Sixteen Swift/BAT GRBs are observed simultaneously by Fermi-LAT. The results of the Swift GRB sample are listed in Table 2. Several of them have the BAT fluence levels comparable to the possible γ-ray transient associated with FRB 131104, but they have GeV emission (also see Figure 2).

3. Discussions

The association between FRB 131104 and the Swift/BAT transient is still controversial (DeLaunay et al. 2016; Shannon & Ravi 2017). The radio-continuum imaging observations of the localization region of the FRB do not find any radio afterglow of this transient (Shannon & Ravi 2017), which puts the cosmic fireball model into question. Nevertheless, since the radio afterglow flux is sensitive to the circumburst medium density, the non-detection of radio emission could be due to a low circumburst density. Given these uncertainties, we tentatively assume that the FRB 131104 or some other FRBs are associated with gamma-ray transients. If the association between FRB 131104 and the Swift/BAT transient is true, the energy of this event would be comparable to cosmological GRBs. Some GRBs with a comparable fluence, such as GRB 110731A, GRB 120729A, and GRB 150512A (see Table 2), have been detected by Fermi-LAT. For comparison, we show, in Figure 2, the relation between the LAT fluences and BAT fluences for those GRBs that were detected by both Fermi-LAT and Swift/BAT. As the BAT transient associated with FRB 131104 has a relatively low fluence in the BAT energy window, it is not surprising that this event was not check whether the Swift GRBs, which have a similar order of magnitude to the prompt fluence level, show any GeV emission. Using the tool gtburst provided in the software package Fermi Science Tools v10r0p5, we carry out a standard maximum likelihood analysis of Fermi-LAT GRB data in the time interval when the main GeV emission radiates. We select events of the TRANSIENT class for a short time interval(<100 s) and the SOURCE class for a longer time

http://Fermi.gsfc.nasa.gov/archive/grb_table/

https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/gtburst.html

Figure 2. Fermi-LAT fluences vs. Swift/BAT fluences for GRBs detected by both instruments. For comparison, the red data are for FRB 131104, which is possibly associated with the Swift/BAT transient.
detected by Fermi-LAT, especially considering that this event enters the FoV of LAT about 5000 s after the radio burst.

Expanding blast waves driven by cosmic fireballs, such as GRBs, may accelerate relativistic electrons through Fermi acceleration, which in turn produce long-term synchrotron emission in the magnetic field, the so-called “afterglows” (Mészáros & Rees 1997; Sari et al. 1998). Assuming a power-law electron distribution with an index of $p$, the flux density of the afterglow synchrotron emission at GeV energies is given by (Kumar & Baniol Duan 2009)

$$F_{\gamma} = \frac{0.2 mJy}{E_{55}^{(p+2)/4} \epsilon_{e}^{-1} \epsilon_{B,-2}^{-1} \gamma_{L,28}^{-3(p-2)/4}} \times \nu_{\gamma}^{p/2} (1+z)^{(p-2)/4} d_L^{128},$$

where $E$ is the isotropic kinetic energy of the blast wave, $\epsilon_{e}$ and $\epsilon_{B}$ are, respectively, the fractions of energy of the shocked gas in electrons and magnetic fields, $\eta \equiv t/10$ s is the time since the beginning of the explosion in the observer frame, $\nu_{\gamma}$ is photon energy in units of 100 MeV, $z$ is the redshift, and $d_L^{128} \equiv d_L/10^{28}$ cm is the luminosity distance to the burst. Using this formula, we can obtain the upper limit of the blast-wave kinetic energy of each FRB, assuming that FRBs are at distances corresponding to the measured DM values and assuming typical reference values for the shock microphysical parameters (i.e., taking $p = 2.4$, $\epsilon_{e} = 0.1$, and $\epsilon_{B} = 0.01$).

With a limit average flux at GeV energies at 5417–11142 s after the radio burst of FRB 131104, we obtain an upper limit of the isotropic kinetic energy of the possible blast wave, i.e., $E_{\gamma} \lesssim 10^{55}$ erg, assuming a luminosity distance corresponding to non-Galactic DM $\Delta 707.9$ pc cm$^{-2}$ that totally arises from intergalactic medium. For our entire FRB sample, we find that the upper limits of blast-wave energy are in the range of $(0.4–190.8) \times 10^{53}$ erg, which are obtained with upper limit GeV fluxes in the range of $(4.7–29.2) \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$. Note that the contribution to the DM of FRBs by their local environment and host galaxy may decrease the value of the luminosity distance. Then, we find that the energy of the blast wave may decrease correspondingly, according to Equation (1). For example, if the real luminosity distance is a half of that inferred from the non-Galactic DM, the upper limit value of the blast-wave energy will decrease by about 70%. Therefore, although current limits obtained for the blast-wave energy are not sufficient to rule out the GRB–FRB connection, future more sensitive observations with Fermi or Imaging Atmospheric Cherenkov Telescopes at TeV energy could be useful to constrain the connection.

4. Summary

It was recently reported that a transient $\gamma$-ray counterpart to the FRB 131104 was discovered in Swift satellite data, which, if true, would increase the energy budget of FRBs to a level comparable to that of cosmological $\gamma$-ray bursts. The relativistic blast wave driven by such an amount of energy may produce multi-wavelength afterglow emission, but searches for radio, optical, and X-ray afterglows from FRB 131104 have so far not resulted in positive detection. It has been argued that the non-detection of radio to X-ray afterglow follows from the fact that the event occurs in a low-density environment (e.g., Dai et al. 2016a; Gao & Zhang 2017; Murase et al. 2017). In contrast, high-energy $\gamma$-ray afterglow flux is not sensitive to the circumburst density, so we searched for possible GeV afterglows of FRBs with Fermi-LAT. While several FRBs were within the FoV of LAT at the burst time, FRB 131104 entered into the LAT FoV only about 5000 s after the radio burst. No GeV emission is found during this period for FRB 131104. For those other FRBs in our sample, we also search for possible GeV emission at the time immediately after the radio burst, but no GeV emission is found either. With the upper limit fluences at GeV energies, we are able to obtain upper limits on the kinetic energy of relativistic blast waves that are possibly associated with these FRBs. The current limits are not stringent enough that they can be used to constrain the connection between FRBs and GRB-like transients. Nevertheless, future more sensitive observations with Fermi or Imaging Atmospheric Cherenkov Telescopes, such as CTA, might be able to constrain the connection.

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7 Tendulkar et al. (2017) reported that the host galaxy of FRB 121102 is at a redshift of $z = 0.19273(8)$. The real luminosity distance is 972 Mpc, which is a fraction of 58% of the inferred luminosity distance ($\approx 1.66$ Gpc) from the non-Galactic DM.
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