Spectral and temporal analysis of short gamma-ray bursts detected by the *Fermi* space telescope with known redshift

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Abstract. Gamma-ray bursts (GRBs) are highly energetic impulses of $\gamma-$rays that are classified into two major categories, namely the long and short GRBs. Their distinction lies in their duration (T_{90}) which is calculated from the photon flux accumulation over time. Long GRBs lasts for more than 2 seconds whilst short GRBs lasts for less than 2 seconds with their prompt emission being in the keV to GeV energy band. Short GRBs are typically spectrally hard and the relation between their duration and spectral index depicts a weak inverse correlation. In this study, a sample of sources with known redshift made up of 15 short GRBs detected by *Fermi* Gamma Ray Burst Monitor (GBM) and one intermediate GRB, GRB100816A were selected for spectral studies in the energy range 10 - 900 keV. Most sources in the sample have photons detected by the *Fermi*-Large Area Telescope (LAT) low energy event (LLE) selection except for GRB090510A which is the brightest source in the sample. As a result it has a considerable number of high energy photons with the highest energy photon energy of 29.9 GeV. The counts obtained from the GBM data were binned and their most prominent pulses were selected for spectral and temporal analysis. Only 12 sources from the sample had prominent pulses including the double peaked GRB111117A. The pulses were fitted using the Norris function. The rise times of the pulses are compared with the rise time of a magnetar giant flare, in order to distinguish between the two γ-ray transients.

1. Introduction

Gamma-ray bursts (GRBs) are among the most luminous sources in the universe [12, 8]. They occur at cosmological distances hence they could be used as cosmological probes. In this study, short GRBs (SGRBs) with 90% of their $\gamma-$ray fluence being in the interval less than 2 seconds (i.e. $T_{90} < 2$ seconds) detected by the *Fermi* telescope are selected. These sources could be treated as cosmological standard candles, similar to Type-Ia supernovae, by using various phenomenological relations among observed parameters [4]. Sources from star forming galaxies are also detected as $\gamma-$ray transients which are not cosmological. These are called magnetar giant flares (MGFs) which are associated with magnetars.

Magnetars are neutron stars (NSs) that are extremely magnetized and are produced by 0.5% of core collapse SNe (CCSNe) [3]. MGFs can be easily mistaken for cosmological SGRBs. For instance, GRB790305 was detected in 1979 which was the first giant flare to be observed [7] hence the aim to further make their criteria clearer. MGFs arise from star forming galaxies and they tend to look like the cosmological hard SGRBs hence fake SGRBs [15] whilst real SGRBs originate from the merging of compact binary systems [5] including NS−NS binary systems, white dwarfs and BH−NS systems.

Fake SGRB pulses depict numerous milliseconds (ms) for their rise time which is much shorter in comparison to cosmological SGRBs [3]. MGFs are however spectrally hard [3] which is similar to the spectral hardness of real SGRBs [2] hence it is often difficult to distinguish between the two. A recent study [13] showed that the T_{90} interval is not sufficient to distinguish between the two hence the attention to the $\gamma-$ray pulse properties. Moreover, MGFs are less energetic compared to their cosmological counterparts having emissions within the energy range $\approx 10^{43} - 10^{46}$ erg [3, 7] whilst the energy of cosmological short bursts can go up to 10^{53} erg .

These mistaken short bursts have posed a number of questions as their variations with cosmological bursts is significant thus their classification should be revised. Zhang et al. [15] asserts that these events are actually different from cosmological short bursts which have varying cosmological progenitors. One characteristic that distinguishes MGFs from cosmological short bursts is their multiple pulse events.

In this work, pulse properties of SGRBs with known redshift which will be referred to as real SGRBs will be used to distinguish them from the fake ones. Removing fake SGRBs will give us a sample of pure NS binary merger events that can be used to study properties of these intriguing sources of electromagnetic and gravitational-wave radiation.

2. Observations and Analysis

In the investigation of finding the distinction between cosmological SGRBs and MGFs a sample of 367 SGRBs with known redshift detected by the *Fermi* Gamma-Ray Burst Monitor (*Fermi* GBM) were selected. *Fermi* GBM is one of the two instruments of the *Fermi* space telescope which also consists of the major instrument; the Large Area Telescope (LAT). *Fermi* LAT is a pair-conversion instrument which is sensitive to γ-rays in the energy range of ≈ 30 MeV to > 300 GeV [2] with a low FoV of 2.4 sr [1].

GBM is the minor instrument which has 14 detectors consisting of 2 BGO and 12 Thallium doped Sodium Iodide (NaI[TI]) scintillation detectors and both detectors are utilised in spectroscopy [2]. The NaI detectors are sensitive in the energy range from 8 keV to 1 MeV and are utilised to obtain a full unocculted view of the sky. In the presence of a GRB event, they get triggered thus can approximate the location of the bursts by using relative count rates [2] making them ideal for triggering and localising GRB events [1]. BGO detectors are best for detecting high energy γ-ray photons and their sensitivity ranges from ≈ 200 keV−40 MeV [2].

The GRB signals in GBM are recorded as three data types; CTIME, CSPEC and TTE. CTIME has a high 256 ms temporal resolution with 8 energy channels [2], CSPEC data has a low 4 s spectral resolution with full spectral resolution of 128 energy channels that are used for spectroscopy [2] and TTE data has a 2μs temporal resolution and 128 energy channel spectral resolution. The temporal resolution can be adjusted to an optimal value with enough statistics during the analysis [2], hence TTE data was utilised in this study.

From the sample consisting of 367 sources, only sources with prominent peaks were of interest. This brought down the number to 16 SGRBs. These sources possessed prominent peaks when their rate counts from different detectors are summed up. However, looking only at the data for each individual detector, some signals were not strong hence their pulses were faint. Therefore, those sources were not considered during pulse fitting and sources with high count rates without the summation of the data were chosen. Hence individual detector data was used instead. This allowed to clearly observe which detectors got triggered hence fit the pulse for the detector that has more counts. These resulted in having a sample of 12 sources. All detectors were chosen based on their rate counts, with the highest one being favourable.

The TTE data was refined using the *RMFIT* package. The background of the data was fitted with a polynomial of degree 1. The 30 - 40 keV energy channel was excluded as it corresponds to the iodine K-edge. The pulses were binned with 16 ms resolution. Finer binnings revealed significant features for GRB 090510 and GRB201221D, see figures 1 and 3.

The pulses were fit with the so-called Norris function [11].

$$I(t) = \begin{cases} A\exp\left[-\left(\frac{|t-t_{peak}|}{t_{rise}}\right)^{\nu_1}\right]; & t < t_{peak} \\ A\exp\left[-\left(\frac{|t-t_{peak}|}{t_{fall}}\right)^{\nu_2}\right]; & t > t_{peak} \end{cases} \tag{1}$$

It is a mathematical function that gives the rising (t_{rise}) and falling times (t_{fall}) of the pulses which are the free parameters. The amplitude of a pulse is given by A and is fixed for each source alongside the pulse peak time t_{peak}, ν_1 and ν_2. The exponential parameters describes the shape of the fit. The former is responsible for the exponential shape whilst the latter is dominant when the fit has a Gaussian shape.

After careful analysis, two sources were removed from the sample consisting of SGRBs with prominent peaks, hence only 10 cosmological SGRB sources were left for analysis. Their analysis was done alongside the recent MGF, GRB200415A. All bursts were analysed in five varying energy channels; 25 - 50, 50 - 100, 100 - 300 and $>$ 300 keV as in the Norris et. al. paper [10] and an addition of 10 - 25 keV energy channel which is the minimum sensitivity of the GBM instrument.

3. Results and discussion

The results of the pulse fitting with the Norris function are summarised in table 1 to table 4. Only the results of 4 brightest SGRBs are presented in this work including that of GRB200415A, the MGF. A typical feature of MGFs is a multi-peaked spectra with a main prominent pulse followed by an oscillating pulse that is weak [15]. The oscillations explain NS rotational period. The rising pulse time of the main prominent pulse is usually tens of ms, see table 2. The fake GRB200415A emerged from a nearby galaxy and its most prominent first pulse was detected which resembles short hard GRBs [6] see figure 2. Hence the the distinction cannot be made from just looking at the spectra. Moreover, SGRB spectra is usually hard [1], which is not an ideal property to differentiate MGFs from cosmological SGRBs as they also have hard spectra. GRB200415A's pulse is non existent in the 10 - 25 keV energy range hence prominent pulses are observed at higher energies.

GRB090510 is a bright short burst with a rising time in the range 22 - 43 ms (see table 1) which does not vary significantly from the 5 - 35 ms rising pulse time of the MGF, GRB200415A (see table 2). The detector selected for GRB090510 was NaI 6 which showed high rate counts amongst others. Although GRB090510 has multiple peaks (see figure 1), the observed multi-peaks are due to the small binnings and have no association with a MGF origin as they are not oscillating nor appear in the background.

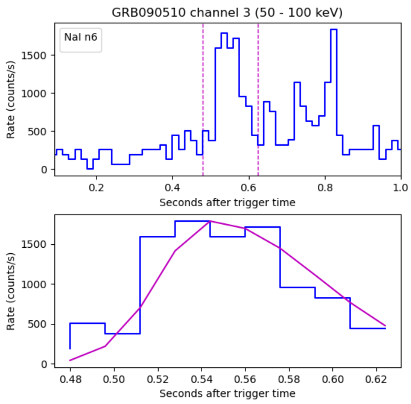

Figure 1. GRB090510, z = 0.903, NaI 6 detector.

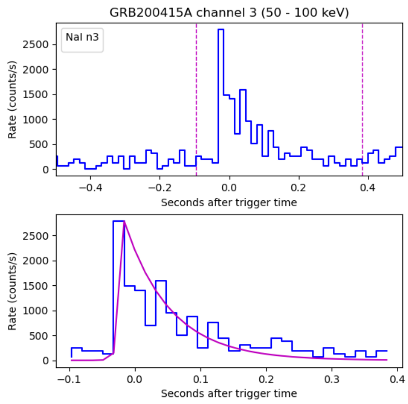

Figure 2. GRB200415A, NaI 3 detector.

Table 1. GRB090510 pulse fit results within the peak interval, 0.480 - 0.624 seconds.

Parameter	Channel number				
	1 (10 - 25 keV)	2 (25 - 50 keV)	3 (50 - 100 keV)	4 (100 - 300 keV)	5 (> 300 keV)
A (counts/s)	1276.99	1211.12	1787.80	2553.98	1213.14
ν_1, ν_2	1,1	1,1	2,2	2,2	1,1
Peak time (s)	0.544	0.528	0.544	0.544	0.544
Rise time (s)	0.043 ± 0.010	0.026 ± 0.009	0.033 ± 0.004	0.031 ± 0.005	0.022 ± 0.005
Fall time (s)	0.090 ± 0.021	0.091 ± 0.023	0.070 ± 0.0073	0.078 ± 0.011	0.063 ± 0.012

The intermediate source, GRB200826A has its duration T_{90} ranging from 1 to 2 seconds as observed with varying detectors [13] therefore, making T_{90} insufficient to distinguish GRBs from MGFs alongside spectral hardness. The sources pulses vary from once energy channel to another hence there is no particular pattern in its rising and falling times from energy channel 1 to channel 5 (table 3). The rising and falling times are a few 100 ms which varies significantly from that of the MGF. The pulses were best fitted with an exponential fit ($\nu_1, \nu_2 = 1, 1$) of the Norris function except for channel 3 which is a combination of Gaussian ($\nu_1 = 2$) and exponential ($\nu_2 = 1$) fit. Table 2 shows that this trend is also shown by the MGF for energy channels 4 and 5.

Table 2. GRB200415A pulse fit results within the peak interval, -0.096 - 0.384 seconds.

Parameter	Channel number				
	1 (10 - 25 keV)	2 (25 - 50 keV)	3 (50 - 100 keV)	4 (100 - 300 keV)	5 (> 300 keV)
A (counts/s)	—	1290.29	2788.55	6549.85	2580.54
ν_1, ν_2	—	1,1	1,1	2,1	2,1
Peak time (s)	—	0.00	-0.016	-0.016	0.00
Rise time (s)	—	0.035 ± 0.009	0.005 ± 0.004	0.010 ± 0.001	0.023 ± 0.003
Fall time (s)	—	0.087 ± 0.014	0.070 ± 0.007	0.061 ± 0.002	0.036 ± 0.004

Table 3. GRB200816A pulse fit results within the peak interval, -0.128 - 0.896 seconds.

Parameter	Channel number				
	1 (10 - 25 keV)	2 (25 - 50 keV)	3 (50 - 100 keV)	4 (100 - 300 keV)	5 (> 300 keV)
A (counts/s)	1911.66	2357.30	2105.26	1973.12	317.30
ν_1, ν_2	1,1	1,1	2,1	1,1	1,1
Peak time (s)	0.496	0.400	0.560	0.448	0.288
Rise time (s)	0.570 ± 0.046	0.327 ± 0.023	0.443 ± 0.017	0.235 ± 0.020	0.103 ± 0.023
Fall time (s)	0.466 ± 0.048	0.409 ± 0.030	0.175 ± 0.015	0.178 ± 0.017	0.235 ± 0.036

Both GRB200415A and GRB201221D have pulse rising and falling times in tens of ms range which is an observed feature of MGFs. The former is a MGF [15] however the latter suggests that it has a MGF origin as opposed to compact binary merger origin [14] due to its maximum pulse rising time of 87 ms, see table 4. Furthermore, the association of GRB201221D with a core-collapse origin is highly improbable [9] hence further raising the question regarding its progenitor.

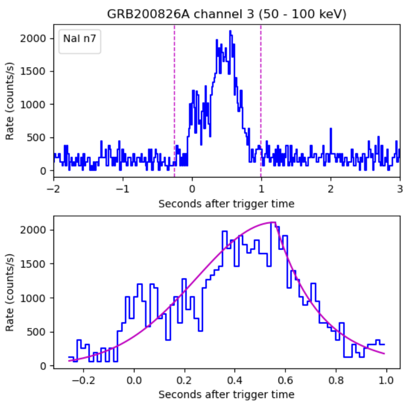

Figure 3. GRB200826A, z = 0.748, NaI 7 detector.

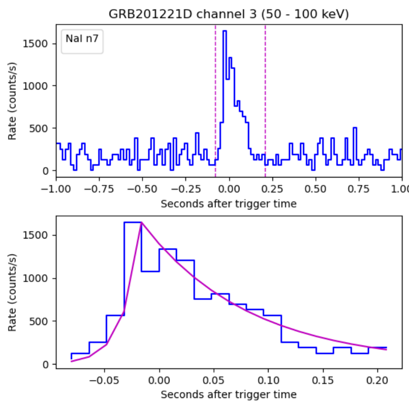

Figure 4. GRB201221D, z = 1.046, NaI 7 detector.

Table 4. GRB202121D pulse fit results within the peak interval, -0.080 - 0208 seconds for n6 detector.

Parameter	Channel number				
	1 (10 - 25 keV)	2 (25 - 50 keV)	3 (50 - 100 keV)	4 (100 - 300 keV)	5 (> 300 keV)
A (counts/s)	1518.99	1203.42	1643.98	1393.80	—
ν_1, ν_2	1,1	1,1	1,1	2,1	—
Peak time (s)	0.016	0.032	-0.016	0.032	—
Rise time (s)	0.047 ± 0.011	0.087 ± 0.016	0.016 ± 0.003	0.070 ± 0.009	—
Fall time (s)	0.106 ± 0.017	0.114 ± 0.016	0.098 ± 0.007	0.051 ± 0.010	—

4. Conclusion

MGFs appear in nearby and star forming galaxies. They are associated with multi-peak signals that oscillate. However they are observed as single peaked sources hence commonly mistaken as cosmological SGRBs. From this work, the pulse fitting mechanism enabled to find the rising time of the pulses and it is observed that GRB200415A depicts a MGF rising time which ranges from 5 to 35 ms. GRB201221D also posses a challenge as it is known to be a cosmological SGRB however its pulse rising time suggests otherwise. GRB200826A's LC pulse profile is protruding (figure 3) and there is no evidence of non-negligible signals outside the main peak hence proving that is it a genuine SGRB. GRB090510 on the other hand depicts multiple pulses, however they are not above the background hence proving that it is also a genuine GRB despite its questionable rising and falling times. For future work, more MGF sources are to be studied including the GRB051103 and GRB070201 amongst other sources. Therefore allowing comprehensive studies on MGFs and cosmological SGRBs properties. [12]

References

[1] M Ajello, M Arimoto, Magnus Axelsson, L Baldini, G Barbiellini, D Bastieri, R Bellazzini, PN Bhat, E Bissaldi, RD Blandford, et al. A decade of gamma-ray bursts observed by fermi-lat: the second grb catalog. *The Astrophysical Journal*, 878(1):52, 2019.

[2] P Narayana Bhat, Charles A Meegan, Andreas von Kienlin, William S Paciesas, Michael S Briggs, J Michael Burgess, Eric Burns, Vandiver Chaplin, William H Cleveland, Andrew C Collazzi, et al. The third fermi gbm gamma-ray burst catalog: the first six years. *The Astrophysical Journal Supplement Series*, 223(2):28, 2016.

[3] E Burns, D Svinkin, K Hurley, Z Wadiasingh, M Negro, G Younes, R Hamburg, A Ridnaia, D Cook, SB Cenko, et al. Identification of a local sample of gamma-ray bursts consistent with a magnetar giant flare origin. *The Astrophysical Journal Letters*, 907(2):L28, 2021.

[4] F Fana Dirirsa, Soebur Razzaque, Frédéric Piron, M Arimoto, Magnus Axelsson, D Kocevski, F Longo, M Ohno, and S Zhu. Spectral analysis of fermi-lat gamma-ray bursts with known redshift and their potential use as cosmological standard candles. *The Astrophysical Journal*, 887(1):13, 2019.

[5] David Eichler, Mario Livio, Tsvi Piran, and David N Schramm. Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars. *Nature*, 340(6229):126–128, 1989.

[6] K Hurley, SE Boggs, DM Smith, RC Duncan, R Lin, A Zoglauer, S Krucker, G Hurford, H Hudson, C Wigger, et al. An exceptionally bright flare from sgr 1806–20 and the origins of short-duration γ-ray bursts. *Nature*, 434(7037):1098–1103, 2005.

[7] EP Mazets, SV Golenetskii, VN Il'Inskii, RL Aptekar, and Yu A Guryan. Observations of a flaring x-ray pulsar in dorado. *Nature*, 282(5739):587–589, 1979.

[8] Peter Meszaros. Gamma-ray bursts. *Reports on Progress in Physics*, 69(8):2259, 2006.

[9] K Misra, DA Kann, KG Arun, A Ghosh, R Gupta, L Resmi, JF Fernández, CC Thöne, A Postigo, SB Pandey, et al. Multi-wavelength analysis of short grb 201221d and its comparison with other high\& low redshift short grbs. *arXiv preprint arXiv:2206.08947*, 2022.

[10] Jay P Norris, Jerry T Bonnell, Demosthenes Kazanas, Jeffrey D Scargle, Jon Hakkila, and Timothy W Giblin. Long-lag, wide-pulse gamma-ray bursts. *The Astrophysical Journal*, 627(1):324, 2005.

[11] JP Norris, RJ Nemiroff, JT Bonnell, JD Scargle, C Kouveliotou, WS Paciesas, CA Meegan, and GJ Fishman. Attributes of pulses in long bright gamma-ray bursts. *The Astrophysical Journal*, 459:393, 1996.

[12] Tsvi Piran. The physics of gamma-ray bursts. *Reviews of Modern Physics*, 76(4):1143, 2005.

[13] A Rossi, B Rothberg, E Palazzi, DA Kann, P DAvanzo, L Amati, Sylvio Klose, Albino Perego, E Pian, C Guidorzi, et al. The peculiar short-duration grb 200826a and its supernova. *The Astrophysical Journal*, 932(1):1, 2022.

[14] Hao-Yu Yuan, Hou-Jun Lü, Ye Li, Bin-Bin Zhang, Hui Sun, Jared Rice, Jun Yang, and En-Wei Liang. Probing the progenitor of high-z short-duration grb 201221d and its possible bulk acceleration in prompt emission. *Research in Astronomy and Astrophysics*, 22(7):075011, 2022.

[15] Hai-Ming Zhang, Ruo-Yu Liu, Shu-Qing Zhong, and Xiang-Yu Wang. Magnetar giant flare origin for grb 200415a inferred from a new scaling relation. *The Astrophysical Journal Letters*, 903(2):L32, 2020.