Measuring the bulk Lorentz factors of gamma-ray bursts in the *Fermi* era

Pak-Hin Thomas Tam[1], Qing-Wen Tang[2], Fang-Kun Peng[3], Xiang-Yu Wang[4]

[1] *School of Physics and Astronomy, Sun Yat-sen University, Guangzhou 510275, China; tanbxuan@mail.sysu.edu.cn*
[2] *School of Science, Nanchang University, Nanchang 330031, China*
[3] *School of Physics and Electronic Science, Guizhou Normal University, Guiyang 550001, China*
[4] *School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China; xywang@nju.edu.cn*

ABSTRACT

Gamma-ray bursts (GRBs) are powered by ultra-relativistic jets. A minimum value of the Lorentz factor of the relativistic bulk motion is obtained based on the argument that the observed high energy photons ($\gg$ MeV) can escape without being attenuated in the pair creation process. With the broad spectral coverage (8 keV to above 300 GeV) of the two instruments onboard Fermi: Large Area Telescope (LAT) and Gamma-ray Burst Monitor (GBM), we systematically search for spectral cutoff features in the time-integrated spectra during the prompt GRB phase for all GRBs detected by the LAT from 2008 August through 2014 October. We found 8 cases with significant signature of cutoff at energies of $\sim 10-500$ MeV (two cases: GRB 090926A and GRB 100724B have been reported earlier). The newest case (GRB 160509A) where such a cutoff is found is also included here. One can obtain the exact value, rather than a lower limit, of the Lorentz factor, assuming that such spectral cutoffs are indeed due to pair creation. We further find that the Lorentz factors are correlated with the isotropic gamma-ray luminosity of the bursts, indicating that more powerful GRB jets move faster.

1. Introduction

The fact that high energy photons ($\gg$ MeV) escape out of the source without suffering from absorption due to pair creation ($\gamma\gamma \leftrightarrow e^+e^-$) is a strong argument for GRBs involving ultra-relativistic outflows (e.g, Krolik& Pier (1991); Lithwick& Sari (2001)). The absorption should cause a spectral cutoff in the highest energy end, which can be probed by the greatly increased spectral coverage and sensitivity of *Fermi* compared to previous gamma-ray instruments.

2. Data analysis and results

We performed a thorough search for cutoff-like spectral features from all GRBs detected by the *Fermi*-LAT from 2008 August through 2014 October, by jointly fitting both LAT and GBM data from the FSSC (Fermi Science Support Center), which together provide a very broad spectral coverage (8 keV to above 300 GeV). The case of GRB 160509A is also considered here (Tam et al. 2017). LAT Low-Energy (LLE; 30–130 MeV) data are also available for 15 bursts, and it turns out that LLE data are crucial in identifying cutoffs because many cutoffs found lie exactly at the LLE range. The joint spectral fitting of GBM/LAT data is performed with RMFIT version 4.3.2, and we quantify the goodness of fit using the Castor Statistic (CSTAT), suitable for small number of photons (especially the case here in the high end of the spectrum).

To search for cutoffs, three spectral models are considered, i.e., Band function, Band function with an exponential cutoff, and the Band function plus a power-law model with an exponential cutoff. We found that in 8 GRBs the spectra deviate from the Band model with ΔCSTAT>28: GRB 090926A, GRB 100724B, GRB 130504C, GRB 130821A,

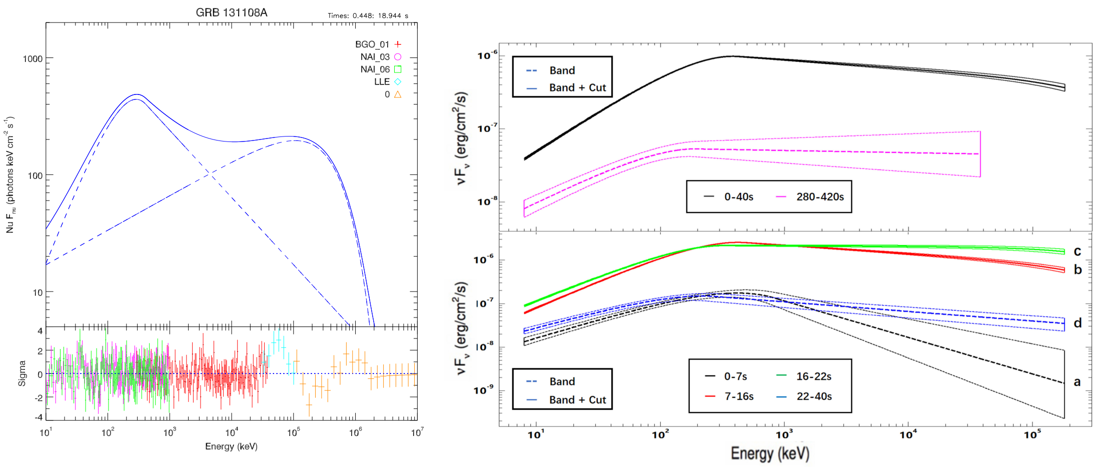

Fig. 1.— Examples of spectral fits, showing high energy cutoffs of GRB 131108A (left, Tang et al. 2015), and GRB160509A (right, Tam et al. 2017).

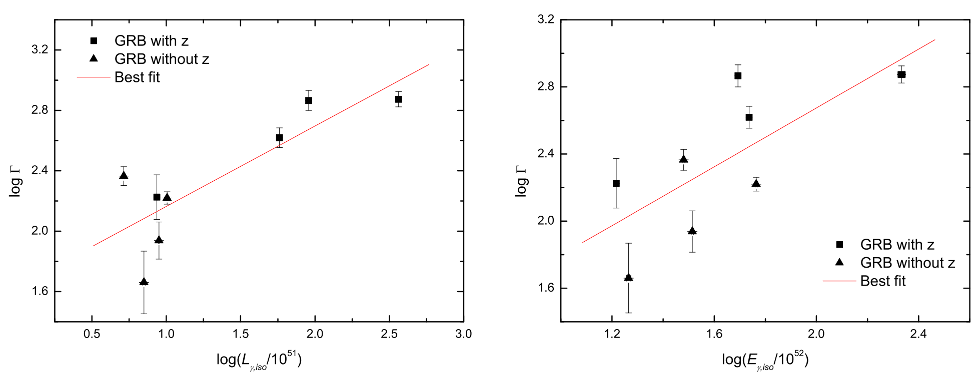

Fig. 2.— The bulk Lorentz factors as a function of the isotropic gamma-ray luminosity (top panel) or isotropic gamma-ray energy (bottom panel) for the 8 bursts with detections of high-energy spectral cutoffs, presented in Tang et al. (2015). GRBs with redshift measurements are marked with squares and those without redshift measurements (then $z = 1$ is assumed) are marked with triangles.

GRB 131231A, GRB 131108A, GRB 140206B and GRB 141028A. The first two cases were reported earlier (Ackermann et al. 2013) and the latter six cases are new findings. The cutoff energies range from about 10 MeV to 400 MeV, as shown in Table 1.

3. Discussion

If the spectral break/cutoff E_c is due to $\gamma\gamma$ absorption within the source, one can compute the bulk Lorentz factor (Γ) of the emitting region by taking $\tau_{\gamma\gamma}(E_c) = 1$. We consider a simple one-zone model where the photon field in the emitting region is uniform, isotropic and time independent in the comoving frame. The target photons that annihilate with photons of energy E_c should have energy above $E_t \gtrsim \Gamma^2(m_ec^2)^2/[E_c(1+z)^2]$, where z is the redshift. For bursts with E_c less than a few hundred MeV, the equal sign holds (i.e., the target photon has similar energy as E_c) and Γ is estimated to be (Li 2010)

$$\Gamma \approx \frac{E_c}{m_ec^2}(1+z). \quad (1)$$

Detailed arguments are given in Tang et al. (2015). We emphasize that Eq. (1) is independent of the central engine and/or energy dissipation models. Essentially the only assumptions here are that the cutoffs are due to pair creation by the target photons coming from the same zone and having similar energy [1]. The results of Γ are presented in Table 1 (taken from Tang et al. 2015). The values of Γ in the sample range from 90 to 900, providing direct evidence that GRBs are powered by ultra-relativistic outflow.

The Lorentz factors can also be determined from the optical/GeV afterglow onset time, when the jet starts to decelerate. However, the values of Lorentz factors derived this way depends on the details of the dynamics and the circumburst environment (e.g., Liang et al. 2010; Ghirlanda et al. 2012, 2018).

Using the original sample used in Tang et al. (2015), we test the relation $\Gamma - L_{\gamma,iso}$ and $\Gamma - E_{\gamma,iso}$, where $L_{\gamma,iso}$ is the averaged, isotropic gamma-ray luminosity in 10-1000 keV and $E_{\gamma,iso}$ is the isotropic gamma-ray energy in 10-1000 keV. For GRBs without redshift, we assumed a redshift of unity. The results are shown in Fig.2. We find the relation

$$\Gamma = 10^{1.65\pm0.20} L_{\gamma,iso,51}^{0.52\pm0.13}, \quad (2)$$

[1] see, however, Gill & Granot (2018), for a numerical calculations that take pair cascades and other effects into account

Table 1: Burst parameters and the derived Lorentz factor of GRBs

GRB	E_c (MeV)	z	$L_{\gamma,iso}$ 10^{50} erg s^{-1}	$E_{\gamma,iso}$ 10^{52} erg	Γ
090926A	350.7 ± 41.3	2.1	365.1 ± 13.7	215.1 ± 8.1	748.3 ± 88.1
100724B	42.4 ± 4	–	10.1 ± 0.1	58.2 ± 0.6	165.9 ± 15.6
130504C	22.2 ± 6.3	–	8.9 ± 0.1	32.7 ± 0.3	86.7 ± 24.5
130821A	13.3 ± 7.3	–	7.1 ± 0.1	18.4 ± 0.3	52.1 ± 28.6
131108A	347.1 ± 52.8	2.4	90.7 ± 1.2	49.4 ± 0.7	734.4 ± 111.7
131231A	61.6 ± 22.5	0.642	8.7 ± 0.1	16.5 ± 0.1	197.9 ± 72.3
140206B	50.1 ± 6.8	–	5.2 ± 0.1	30.2 ± 0.4	196.1 ± 26.6
141028A	53.2 ± 7.3	2.332	57.7 ± 1.3	54.5 ± 1.2	346.9 ± 47.6
160509A	72.2 ± 10.6	1.17	$\sim$720	$\sim$106	307 ± 45

with a Pearson correlation coefficient of $r = 0.844$ and null hypothesis probability of 0.008, indicating a positive correlation. Similarly, we find

$$\Gamma = 10^{1.01\pm0.56} E_{\gamma,iso,52}^{0.88\pm0.35}, \tag{3}$$

with a Pearson correlation coefficient of $r = 0.707$ and null hypothesis probability of 0.050 (Tang et al. 2015).

GRB jets are accelerated at the early stage while the internal energy of the fireball is gradually converted to the kinetic energy. After the acceleration, the jet is expected to have the Lorentz factor which is equal to the initial dimensionless entropy $\eta = L_0/(\dot{M}c^2)$, where L_0 and $\dot{M}$ are the total energy and mass outflow rates, respectively. Using Eq.2, the mass outflow rate follows: $\dot{M} \propto L_{\gamma,iso}^{0.48\pm0.13}$ (assuming that $L_{\gamma,iso} \propto L_0$). This puts useful constraints on any central engine models of GRBs (Tang et al. 2015).

P.-H. T. T. is supported by NSFC through grants U1731136, 11633007 and 11661161010. We also acknowledge the strategic cooperation of Sun Yat-sen University and ICRANet.

REFERENCES

Ackermann, M.,Ajello, M., Asano, K., et al. 2013, ApJS, 209, 11

Ghirlanda, G., Nava,L., Ghisellini, G., et al. 2012, MNRAS, 420, 483

Ghirlanda, G., Nappo, F., Ghisellini, G., et al. 2018, A&A, 609, A112

Gill, R., & Granot, J. 2018, MNRAS, 475, L1

Krolik, J. H., & Pier, E. A. 1991, ApJ, 373, 277

Li, Z. 2010, ApJ, 709, 525

Liang, E.-W., Yi, S.-X.,Zhang, J., et al. 2010, ApJ, 725, 2209

Lithwick, Y., & Sari, R. 2001, ApJ, 555, 540

Tam, P.-H. T., He, X.-B., Tang, Q.-W., & Wang, X.-Y. 2017, ApJ, 844, L7

Tang, Q.-W., Peng, F.-K., Wang, X.-Y., & Tam, P.-H. T. 2015, ApJ, 806, 194