Evaluating the Bulk Lorentz Factors of Outflow Material: Lessons Learned from the Extremely Energetic Outburst GRB 160625B

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Abstract

GRB 160625B is an extremely bright outburst with well-monitored afterglow emission. The geometry-corrected energy is high, up to $\sim 5.2 \times 10^{52}$ erg or even $\sim 8 \times 10^{52}$ erg, rendering it the most energetic GRB prompt emission recorded so far. We analyzed the time-resolved spectra of the prompt emission and found that in some intervals there were likely thermal-radiation components and the high energy emission was characterized by significant cutoff. The bulk Lorentz factors of the outflow material are estimated accordingly. We found out that the Lorentz factors derived in the thermal-radiation model are consistent with the luminosity-Lorentz factor correlation found in other bursts, as well as in GRB 090902B for the time-resolved thermal-radiation components, while the spectral cutoff model yields much lower Lorentz factors that are in tension with the constraints set by the electron pair Compton scattering process. We then suggest that these spectral cutoffs are more likely related to the particle acceleration process and that one should be careful in estimating the Lorentz factors if the spectrum cuts at a rather low energy (e.g., $\sim$ tens of MeV). The nature of the central engine has also been discussed, and a stellar-mass black hole is favored.

Key words: gamma-ray burst: individual (GRB 160625B) – methods: data analysis – radiation mechanisms: thermal

1. Introduction

The outflows of gamma-ray bursts (GRBs) are generally considered to move relativistically to solve the compactness problem (Piran 1999; Kumar & Zhang 2015). However, the Lorentz factor of the outflow is not an observable quantity. Several methods have been proposed to estimate the Lorentz factor ($\Gamma$) based on different hypotheses or fireball models: a lower limit can be obtained by requiring that the Lorentz factor be large enough to make the observed most energetic photon, not to annihilate (Krolik & Pier 1991; Fenimore et al. 1993; Woods & Loeb 1995; Baring & Harding 1997). If cutoffs are observed on the high end of the spectra of prompt emissions, the exact values of the Lorentz factor rather than lower limits can be derived by assuming the optical depth equals unity for photons with cutoff energies (Lithwick & Sari 2001; Ackermann et al. 2011; Tang et al. 2015). Thermal components that accompany the underlying nonthermal emissions in several GRBs are thought to originate from the photosphere of fireballs; thus they can also be used to determine the Lorentz factors (Pe’er et al. 2007; Ryde et al. 2010; Fan & Wei 2011; Zou et al. 2015). Note that these approaches are valid for the time-resolved outflow material, as long as the spectra can be reliably measured. Another kind of method is to model the multi-wavelength afterglow based on the dynamics of the fireball. In the thin shell case, the reverse shock is weak and the optical/X-ray emission is dominated by the forward shock emission with an almost constant Lorentz factor. Hence the peak of the optical/X-ray emission marks the deceleration of the fireball and can probe the Lorentz factor robustly (Meszaros & Rees 1993; Jin & Fan 2007; Molinari et al. 2007; Xue et al. 2009; Liang et al. 2010, 2015). In the thick shell case, the reverse shock is strong and the Lorentz factor can be determined by a self-consistent modeling of the optical flash, as well as the later afterglow emission (Sari & Piran 1999; Wang et al. 2000; Fan et al. 2002; Soderberg & Ramirez-Ruiz 2002; Kobayashi & Zhang 2003; Zhang et al. 2003). The quiet periods of the prompt gamma-ray/X-ray emission have also been used to set upper limits on some GRB material (Zou & Piran 2010). These approaches can be used to measure the “averaged” Lorentz factor of the total GRB outflow material.

All of these methods have their own disadvantages, such as the ambiguity on variability timescale, dependence on other uncertain quantities (e.g., the radiation efficiency), and the assumption on the microphysical parameters as well as the environment. It is worthwhile to compare the Lorentz factors derived in different ways. For such a purpose, at least two observational features (i.e., high energy cutoff, thermal component, the well-behaved rising of the forward shock afterglow, or the distinct reverse shock optical flash) are needed for the same event. Such a request is unsatisfied in most cases. In this work, we study one specific case-GRB 160625B, a burst that is so bright that the spectrum can be well measured in very short time intervals and the Lorentz factors of the fireball shells can be derived in a few approaches. In Section 2 we perform the spectrum analysis of GRB 160625B. In Section 3 we calculate the Lorentz factors from high energy cutoffs and the possible thermal component found in GRB 160625B, and compare them in the $\Gamma-L_{\gamma}$ relation with other bursts (where $L_{\gamma}$ represents the luminosity of the prompt emission). In Section 4 we summarize our results, with some discussion.
2. Data Analysis

2.1. Observations

GRB 160625B first triggered Fermi GBM at 22:40:16.28 UT on 2016 June 25 (Burns 2016). About 188 s later Fermi/LAT was triggered by a bright pulse from the same GRB, and the onboard location is R.A., decl. = 308.3, 6.9 (J2000; Dirirsa et al. 2016). This pulse accompanied very bright pulses seen by GBM. The Fermi GBM was triggered at 22:51:16.03 UT for the second time for this burst (Burns 2016). Other gamma-ray telescopes, including Konus–Wind (Svinkin et al. 2016) and CALET (Yamaoka et al. 2016), also reported the detection of GRB 160628B. Swift/XRT has performed follow-up observations of this burst (Melandri et al. 2016), and to date an afterglow of ~10^6 s has been detected. There are also fruitful optical observations on the afterglow (Batsch et al. 2016; Cobb 2016; D’Elia et al. 2016; Gorbovskoy et al. 2016; Karpov et al. 2016; Kuroda et al. 2016; Mazaeva et al. 2016c; Moskvitin 2016; Oates & D’A 2016; Troja et al. 2016; Xu et al. 2016). Xu et al. (2016) reported a redshift of 1.406 measured by the VLT/X-shooter, which was then confirmed by TNG (D’Elia et al. 2016). The isotropic-equivalent energy corresponding to this redshift is ~5 × 10^54 erg in Konus–Wind’s energy band (Svinkin et al. 2016). The afterglow of GRB 160625B is also detected on near-infrared (NIR) and 15 GHz radio band (Mooley et al. 2016; Watson et al. 2016).

In this work we mainly focus on analyzing the gamma-ray data from the Fermi satellite to investigate the properties of prompt emission, yet we will also have discussion about results from other observations.

2.2. Data Selection

We extract the GBM data, the standard LAT data, as well as the LAT low energy (LLE) data of GRB 160625B from the Fermi Science Support Center (FSSC). For GBM data, we choose three NaI detectors that have the smallest angles from individual detectors’ boresight to the GRB when the burst was triggered, and the choice of BGO detector is based on the position corresponding to the selected NaI detectors. We use the time-tagged events (TTE) data files that contain individual photons with time and energy tags, and they cover a time range from ~140 s before T0 (the GBM first trigger time) to ~480 s after T0. For LAT data, we use the FITS files generated by the LAT Low-Energy Events Catalog Server. It contains the events passing the LLE CUT and has already been binned in energy and time, with 1 s resolution, and covers a time range of (~1000 s, 1000 s) with respect to T0. In the following joint spectral analysis we combine LLE data (30 MeV–1 GeV) and the GBM data (10–800 keV for NaI detectors and 200 keV–40 MeV for BGO detector) in the fitting.

2.3. Spectral Fitting

Herein we perform the joint spectral analysis using RMFIT version 4.3.2. Our aim is to extract the time-resolved spectra and to search for the potential cutoff and black body components in prompt emission; the reasons and criteria for the division of time intervals are described as follows.

First, the time intervals of each spectrum should have a strong gamma-ray signal detected over the background for all the selected detectors at the same time. Since there are much less photons at high energy end, the time division mainly depends on the LLE data. We set the minimum count rate for LLE data to be 40 counts s^{-1}, and this lead to a time span of 186–203 s for GRB 160625B with respect to T0. Second, we divide the time span into several intervals: initially, we divide the time span into 1 s bins; then we combine the bins which have less than 200 LLE counts with the next one. Following these steps, we finally get eight time intervals (see the first column of Table 1).

Initially, we fit each spectrum with a Band function (Band et al. 1993) as the baseline. Then, we add high energy cutoff and black body components into the model to see how they improve the fit. We consider the cutoff on the high energy end of band function; therefore, we have the following models for comparison:

1. Band function

\[ N_{\text{band}}(E) = \begin{cases} \frac{A(E/100)^\alpha \exp(-E(2 + \alpha)/E_p)}{E_p} & \text{if } E < E_p \\ \frac{A \left\{ \left(\alpha - \beta\right)E_p/[100(2 + \alpha)] \right\}^{\alpha - \beta} \times \exp(\beta - \alpha)(E/100)^\beta}{E_p} & \text{if } E \geq E_p, \end{cases} \]

where \[ E_p = (\alpha - \beta)E_p/(2 + \alpha). \]

2. BandC model (i.e., the Band function with a high energy cutoff)

\[ N_{\text{BandC}} = N_{\text{band}} \exp(-E/E_c), \]

3. Band + BB (Band with a black body component)

\[ N_{\text{Band+BB}} = N_{\text{Band}} + A_1 \frac{E^2}{\exp(E/kT) - 1}. \]

4. BandC + BB

\[ N_{\text{BandC+BB}} = N_{\text{BandC}} + A_2 \frac{E^2}{\exp(E/kT) - 1}. \]

The uncertainties caused by inter-calibration between the GBM and the LAT are taken into account, by adding an Eff. Area Corr. term in RMFIT (Ackermann et al. 2013). The correction factors are allowed to vary from 0.9 to 1.2 for NaI and BGO detectors, while fixed to 1 for LAT LLE.

The Castor statistic (CSTAT) is chosen as the fitting statistic, since it is suitable for Poisson data, which is the case for energy bins at the high end.

We summarize the CSTAT of the four models for each of our spectra in Table 1, and will discuss the results in the next section.

2.4. Fitting Result

As described in the previous section, we fit the time-resolved spectra of GRB 160625B with four different models. These models have different numbers of free parameters. In general, introducing more parameters will improve the fit, but one should also be aware that a complex model may overfit the data. To judge the most appropriate models that felicitously describe the data, we introduce the Bayesian information criterion (BIC). The BIC was developed by Gideon E. Schwarz

| Model   | CSTAT | BIC   |
|---------|-------|-------|
| Band    |       |       |
| BandC   |       |       |
| Band+BB |       |       |
| BandC+BB|       |       |

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the lowest BIC is preferred. The BIC is defined as (Schwarz 1978)
\[
\text{BIC} = -2 \ln \mathcal{L} + k \ln (N),
\]
where \( \mathcal{L} \) is the likelihood of the best-fit model, \( k \) is the number of free parameters, and \( N \) is the number of data points, respectively. The \( \text{CSTAT} \) in our fit can be converted to likelihood by \( \text{CSTAT} = -2 \ln \mathcal{L} \). We compute the BIC for the four models and list them in Table 1. When comparing a model against another model with higher BIC, \( \Delta \text{BIC} \) of 2–6 represents a positive evidence, \( \Delta \text{BIC} \) of 6–10 represents a strong evidence, and \( \Delta \text{BIC} > 10 \) represents very strong evidence of improvement (Kass & Raftery 1995). We note that the BIC compares models from pure statistical perspective; one should also consider the physical interpretation of models and the reasonable range of their parameter values.

By applying the criterion described here, we find that the fits are improved significantly (\( \Delta \text{BIC} > 10 \)) after adding extra components (i.e., the cutoff or black body components) into the model, compared to fitting the spectra with band function alone for all eight time intervals. The Band + BB model has the lowest BIC in six intervals, while the BandC model and Band + BB model have the lowest BIC in 186–188 s and 191–195 s, respectively. During 201–203 s, although the BandC + BB model has the lowest BIC, it is comparable with the Band + BB model (\( \Delta \text{BIC} < 2 \)), and the cutoff energy is poorly constrained (295 ± 175 MeV). Thus we prefer the Band + BB model rather than the BandC + BB model to represent the spectral shape for this interval. Extra power law components are found in some GRBs; for completeness, we have also included the models with this component in the comparison. However, it did not improve the fit significantly.

As mentioned previously, the BIC compares models from a pure statistical perspective. Although adding a thermal component into the model significantly improves the fit in seven out of eight time intervals, we do not claim a clear detection of thermal components in GRB 160625B for the following reasons: first, the thermal components are just subdominant in all seven intervals (i.e., they just account for \( \sim 14\%–28\% \) total luminosities); second, there may be strong spectral evolution within a timescale of 1 s (which is the smallest scale of our time bins that is limited by the LLE data). The superposition of Band functions with different \( E_{\text{peak}} \) may also lead to a variant on the shape of the time-average spectrum. To further examine the presence of thermal components, we divided the two brightest time intervals (188–189 and 189–190 s) into ten 0.2 s bins, and fit the data of n9 and b1 detectors with Band and Band + BB models. (We ignore the LLE data, since the LLE data of this burst are insufficient for such a short time bin and the possible thermal components are not within the energy range of LLE data.) The result shows that in three bins there is very strong evidence, in two bins we have strong evidence, and in another two bins we have positive evidence of improvement of the fit after adding the black body component according to the BIC. The other three bins are the least bright ones, and their BGO data above 2000 keV are mostly upper limits, so it is hard to constrain an extra component located on the high energy end of the Band function.

To summarize the fitting result of GRB 160625B, we found cutoffs of tens of MeV in six out of eight intervals, and the evidence of thermal radiation in seven out of eight intervals; the evidence of thermal radiation component still exists, even in 0.2 s resolution for the two brightest intervals. We present the models we prefer for the eight intervals in Table 1 and Figure 1, and our following calculations are based on the parameters of these preferred models listed in Table 2.

### Table 1
Comparison of the Goodness of Fit for Different Models

| Time (s) | Band | BandC | Band + BB | BandC + BB | Preferred Model |
|---------|------|-------|-----------|------------|----------------|
| 186–188 | 573.9 (598.5) | 464.1 (494.8) | 499.7 (536.7) | 461.5 (504.6) | BandC |
| 188–189 | 841.0 (865.6) | 588.0 (618.8) | 708.6 (745.5) | 544.4 (587.5) | BandC + BB |
| 189–190 | 904.2 (928.7) | 759.5 (790.2) | 696.4 (733.3) | 644.9 (687.8) | BandC + BB |
| 190–191 | 672.1 (696.6) | 633.9 (664.5) | 607.6 (644.3) | 573.0 (615.9) | BandC + BB |
| 191–195 | 826.2 (850.9) | 826.3 (857.1) | 698.2 (735.2) | 697.7 (740.9) | Band + BB |
| 195–200 | 828.2 (852.9) | 820.9 (851.7) | 751.1 (788.1) | 716.5 (759.7) | BandC + BB |
| 200–201 | 728.0 (752.6) | 577.9 (608.6) | 621.6 (658.5) | 560.1 (603.2) | BandC + BB |
| 201–203 | 606.3 (630.9) | 604.5 (635.2) | 578.5 (615.4) | 570.7 (613.8) | Band + BB |

### Table 2
Best-fit Parameters of the Assumed Models

| Time (s) | Model | \( \alpha \) | \( \beta \) | \( E_{\text{peak}} \) (keV) | Temperature (keV) | \( E_c \) (MeV) |
|---------|-------|------------|-----------|-----------------|-----------------|-----------|
| 186–188 | BandC | -0.79 ± 0.01 | -1.61 ± 0.02 | 1091 ± 69 | ... | 15.26 ± 2.50 |
| 188–189 | BandC + BB | -0.54 ± 0.01 | -1.75 ± 0.01 | 572 ± 17 | 389.0 ± 7.92 | 19.15 ± 2.45 |
| 189–190 | BandC + BB | -0.60 ± 0.01 | -2.31 ± 0.01 | 613 ± 10 | 657.3 ± 10.8 | 58.77 ± 18.4 |
| 190–191 | BandC + BB | -0.59 ± 0.01 | -2.16 ± 0.02 | 353 ± 9 | 290.5 ± 6.32 | 41.43 ± 13.5 |
| 191–195 | Band + BB | -0.60 ± 0.01 | -2.58 ± 0.02 | 320 ± 10 | 243.1 ± 10.4 | ... |
| 195–200 | BandC + BB | -0.60 ± 0.01 | -2.38 ± 0.02 | 319 ± 6 | 206.1 ± 1.95 | 34.08 ± 10.1 |
| 200–201 | BandC + BB | -0.60 ± 0.01 | -1.91 ± 0.02 | 459 ± 17 | 250.4 ± 5.30 | 32.53 ± 5.74 |
| 201–203 | Band + BB | -0.66 ± 0.02 | -2.56 ± 0.03 | 416 ± 25 | 260.2 ± 16.1 | ... |
3. Model-dependent Estimates of the Lorentz Factors of the Outflow Material

In this section we compute the Lorentz factors using the high energy cutoffs and thermal radiation components obtained in Section 2, and then test the correlation between the Lorentz factor and the rest frame isotropic gamma-ray luminosity ($\Gamma L$) using our results, and compare them with other works.

3.1. Evaluating the Lorentz Factor

3.1.1. The Cutoff Model

For GRB 160625B, since we have found high energy cutoffs in time-resolved spectra in six intervals, we can calculate the Lorentz factors for these intervals and explore how they evolve. Assuming the cutoffs are caused by the $\gamma\gamma$ absorption, the Lorentz factor $\Gamma$ can be derived by Lithwick & Sari (2001):

$$\Gamma = \frac{\gamma + 1}{(\gamma - 1)(\gamma - 2)} \left( \frac{E_c}{m_e c^2} \right)^{(\beta - 1)/(\beta - 2)} \left( 1 + z \right)^{(\beta - 1)/(\beta - 2)},$$

(1)

where $\beta$ is the high energy index of Band function, $z$ is the redshift, and $E_c$ is the cutoff energy. Numerically, $\hat{\Gamma}$ can be calculated by Lithwick & Sari (2001),

$$\hat{\Gamma} = \left( 2.1 \times 10^{12} \right) \left[ \frac{df_c/\gamma \text{ Gpc}^2 (0.511)^{\gamma + 1}}{\delta T/0.1 \text{ s} (\gamma - 1)} \right],$$

where $f_c$ is the observed number of photons per second per square centimeter per MeV at the energy of 1 MeV, and $\delta T$ is the variability timescale.

We find that the cutoff energies are relatively low (e.g., ~tens of MeV). When using Equation (1) to derive the Lorentz factor, it is assumed that the photons with energy $E_c$ can annihilate a second photon whose energy is much less than $E_c$ (i.e., $E_c \gg \gamma^2 m_e^2 c^2 / \left| (E_c (1 + z)^2) \right|$). If this is not satisfied, Equation (1) is no longer valid, since the spectrum of target photons cannot be described by a power law parameterized by $\beta$ (the high energy index of band function). In this case, we can only assume that the photons with energies around $E_c$ annihilate with target photons, with energies comparable to themselves, and then the Lorentz factor is estimated by

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

(2)

The Lorentz factors derived from the opacity hypothesis are shown in Table 3. However, another limitation on the Lorentz factor should be considered when $E_c$ is low. The electron-positron pairs produced by photon annihilation can in turn Compton scatter other photons, which sets a lower limit on the Lorentz factor (Lithwick & Sari 2001):

$$\Gamma > \frac{1}{2} \left( 1 + \frac{1}{2} \right) \left( \frac{1}{2} \right)^{1/4},$$

and if this limit is unsatisfied, the burst would be optically thick to all photons (Lithwick & Sari 2001). We calculate this limit for all our spectra with a cutoff and list them in Table 3. Surprisingly, the lower limits are much (about an order of magnitude) higher than the Lorentz factors derived from the opacity hypothesis for GRB 160625B. The inconsistency of the results from the two methods implies that the spectral cutoffs of GRB 160625B are unlikely caused by pair production of high energy photons. There is an additional argument disfavoring the absorption hypothesis. As found in the numerical simulations (e.g., Pe’er & Waxman 2004), in order to have an exponential cutoff due to absorption, one would need an absorbing screen through which the radiation propagates. While in reality the absorption and emission processes are coexisting, with a proper radiation transfer the observed absorption feature is a break in the power-law slope, not an exponential cutoff (Pe’er & Waxman 2004).

3.1.2. The Thermal Radiation Model

The measurements of the temperature and flux of the thermal components also allow the determination of the fireball shells’ Lorentz factor. We evaluate the Lorentz factor by Pe’er et al. (2007),

$$\Gamma = \left[ \frac{(1.06)(1 + z)^2 dT}{2 m_p c^3 R} \right]^{1/4},$$

(3)

where $F_{\text{ob}}$ is the observed total energy flux, $Y$ is the ratio between the total fireball energy and the energy emitted in gamma-rays, and $R$ is defined as $R = \left( \frac{F_{\text{bb,ob}}}{\sigma_T} \right)^{1/2}$, where $F_{\text{bb,ob}}$ and $T_{\text{ob}}$ are the observed blackbody component flux and temperature, respectively. Meanwhile, three relevant radii—the initial fireball radius $r_0$, the saturation radius $r_s$, and the

Table 3

| Time  | $L_{BB}/10^{52}$ | $\Gamma_{\text{Cut}}$ | $\Gamma_{\text{BB}}/Y^{1/4}$ | $\Gamma_{\text{lim}}$ | $r_0/Y^{-3/2}$ | $r_s/Y^{-5/4}$ | $r_s/Y^{3/4}$ | $M_{\text{lim}}/Y^{-3/2}$ |
|-------|------------------|-----------------------|-----------------------------|-----------------------|----------------|----------------|----------------|-----------------------------|
| (s)   | (erg/s)          |                      |                             |                       | (10^14 cm)     | (10^15 cm)     | (10^14 cm)     | (M_\odot)         |
| 188–189 | 84.52           | 90.17 ± 11.54         | 1656.35                     | 924.78                | 0.52           | 0.86           | 2.63           | 17.65           |
| 189–190 | 78.43           | 276.71 ± 86.63        | 2022.59                     | 485.49                | 0.41           | 0.83           | 1.34           | 13.94           |
| 190–191 | 32.48           | 195.07 ± 63.95        | 1215.12                     | 462.60                | 1.18           | 1.43           | 2.56           | 39.80           |
| 191–195 | 18.60           | 1018.72               | ...                         | ...                   | 1.68           | 1.71           | 2.49           | 57.00           |
| 195–200 | 21.87           | 160.46 ± 47.55        | 933.71                      | 337.52                | 3.78           | 3.53           | 3.80           | 127.87          |
| 200–201 | 58.61           | 153.16 ± 27.03        | 1274.04                     | 695.07                | 0.99           | 1.26           | 4.01           | 33.48           |
| 201–203 | 25.65           | ...                   | 1113.60                     | ...                   | 1.36           | 1.51           | 2.63           | 46.04           |

Note. $\Gamma_{\text{Cut}}, \Gamma_{\text{BB}}, \Gamma_{\text{lim}}$, and $M_{\text{lim}}$ represent the Lorentz factor derived from the cutoffs, the Lorentz factor derived from the thermal component, the lower limit of Lorentz factor derived from the Compton scattering effect, and the lower limit for the mass of central black hole, respectively.
photospheric radius \( r_{\text{ph}} \)—can be obtained by Pe’er et al. (2007):

\[
r_0 = \frac{4^{3/2}}{(1.48)^6(1.06)^4} \frac{d_L}{(1 + z)^2} \left( \frac{E_{\text{bb,ob}}}{YF_{\gamma,\text{ob}}} \right)^{3/2} R,
\]

\[
r_\gamma = \Gamma r_0,
\]

\[
r_{\text{ph}} = \frac{E_{\text{tot}} \sigma_T / 8 \pi \Gamma^3 m_p c^3}{L_{\gamma}},
\]

where the total energy of the fireball \( E_{\text{total}} \) can be estimated by \( E_{\text{total}} = \pi d_L^2 Y F_{\gamma,\text{ob}} \). With Equations (3)–(6), we calculate \( \Gamma, r_0, r_\gamma, \) and \( r_{\text{ph}} \) for the seven intervals of GRB 160625B that are likely to host thermal components, and the results are also summarized in Table 3. For these calculations, it is assumed that the blackbody components in different intervals are dominated by thermal emissions from independent shells, and the high latitude emission from the previous interval is not considered. Note that in the previous approach we adopt an analytic approximation that the outflow accelerates linearly at first and then moves in a constant speed after reaching the saturation radius. The actual transition could be much smoother (see Piran 1999, and the references therein), likely affecting the estimates of the Lorentz factor and the nozzle radius. In the current scenario, usually we have \( r_{\text{ph}} \sim n \times r_\gamma \) for a reasonable \( Y \sim 4 \) (see Table 3), and hence the analytic approximation seems reasonable.

We find that the \( \Gamma \) derived from blackbody components distributes from 900 to 2000, which is much higher than that derived from the spectral cutoffs of tens of MeV, and is satisfied with the limitation set by the Compton scattering effect. This again suggests the cutoffs in GRB 160625B are not caused by the pair production effect. An upper limit of central engines mass can be set by assuming the initial fireball radius is, of course, outside the Schwarzschild radius of the central black hole; then the upper limit is derived by \( m < (r_0 c^2/2G) Y^{-3/2} \). We plot the upper limits derived from different intervals of GRB 160625B with different \( Y \) in Figure 2. If \( Y \) is larger than 4 in the first two time intervals, the black hole’s mass will be lower than \( 2 \times 10^9 \text{M}_\odot \), which is lower than the maximal gravitational mass of neutron stars measured so far.

### 3.1.3. Correlations

Correlations involving \( \Gamma \) are widely discussed in the literature, since they give important clues to reveal the physics of GRB. Liang et al. (2010) found a tight correlation between \( \Gamma \) and isotropy gamma-ray energy \( E_\gamma \). Lü et al. (2012) extended the sample and found another tight correlation of \( \Gamma \propto L_\gamma^{0.5} \). Later, Fan et al. (2012) showed that the time-resolved thermal emissions of GRB 090902B also follow the \( \Gamma \propto L_\gamma \) correlation. We test this relation with our results, and also include the samples from Tang et al. (2015) in Figure 3. The gray points and gray solid line are samples from Lü et al. (2012) and the empirical correlation they derived, respectively. We find that the Lorentz factors derived from the thermal components show a tight positive correlation with \( L_\gamma \) (with a Pearson correlation coefficient of 0.91, irrelevant to the value of \( Y \) in Equation (3)). The red triangles in Figure 3 are calculated with Equation (3) by setting \( Y = 1 \) (corresponding to a very high radiation efficiency case). We find that the sequence in GRB 160625B is very similar to the one in GRB 090902B (blue triangles). Fitting these two sequences respectively, we obtain the slope of \( 0.40 \pm 0.08 \) for GRB 160625B (red dashed line) and \( 0.39 \pm 0.03 \) for GRB 090902B (blue dashed line), which are consistent with each other within the errors. On the other hand, the data of GRB 160625B in Figure 3 also follow the sequence for different bursts obtained by Lü et al. (2012). We note that although the slope they derived is \( 0.29 \pm 0.002 \), the relatively large dispersion (with a Pearson correlation coefficient of 0.79; Lü et al. 2012) would lead to a change of slope for different groups of samples.

The green dots in Figure 3 are derived from a \( \gamma \gamma \) opacity hypothesis that does not satisfy the lower limits (blue arrows) set by Compton scattering effect, and it is clear that they do not show a \( \Gamma \propto L_\gamma \) correlation.

#### 3.1.4. Information from the Afterglow

As mentioned in Section 2, the follow-up observations from radio to X-ray band can also be utilized to infer information about the outflow.

Swift/XRT began to observe the afterglow 10,000 s after the trigger (Melandri et al. 2016). Although the onset of the afterglow was not seen, due to the relatively late start time of observation, one can still obtain a lower limit for the Lorentz factor by requiring that the outflow is fast enough to produce the onset before the observation time. Assuming the afterglow of GRB 160625B is in the thin shell case and the environment is homogeneous, the lower limit can be derived by (Sari & Piran 1999)

\[
\Gamma > 193 (m\eta) ^{-1/8} \times \left( \frac{E_{\gamma,52}}{t_{p,z,2}} \right)^{1/8} \tag{7}
\]

We collect the total fluence of GRB160625B from FSSC and K-corrected (Bloom et al. 2001) it into the rest frame isotropic-equivalent gamma-ray energy \( E_\gamma \), in a 1–10,000 keV band. The \( E_\gamma \) are found to be \( 9.20 \pm 0.02 \times 10^{54} \text{erg} \), which is very high among GRBs. We take the radiation efficiency \( \eta = 0.5 \) and the circumburst density \( n = 0.1 \text{ cm}^{-3} \). Let \( t_{p,z,2} \) equal the start time of XRT observation in the rest frame; the lower limit derived from Equation (7) is 164.5. We note that the limitation here is for the bulk Lorentz factor of the merged shells that crashed into the surrounding medium, while the Lorentz factors or limitations derived from the previous sections are for the independent shells before they merged.

Another important phenomenon observed by Swift/XRT is the jet break of X-ray afterglow at late time. We use the light curve analysis result from the UK Swift Science Data Centre, in which the jet break time is determined to be \( 1.8 \pm 0.5 \times 10^8 \text{ s} \) (Evans et al. 2007, 2009). With the isotropic energy \( E_\gamma \) and the jet break time \( t_j \), the half-opening angle of the jet can be estimated by (Sari & Piran 1999; Frail et al. 2001)

\[
\theta_j \approx 0.057 \left( \frac{t_j}{1 \text{ day}} \right)^{3/8} \left( \frac{1 + z}{2} \right)^{-3/8} \left( \frac{E_\gamma}{10^{53} \text{ erg}} \right)^{-1/8} \times \left( \frac{\eta}{0.2} \right)^{1/8} \left( \frac{n}{0.1 \text{ cm}^{-3}} \right)^{1/8} \tag{8}
\]

We still assume \( \eta \) and \( n \) to be 0.5 and 0.1, respectively; then we obtain \( \theta_j = 0.106 \text{ rad} \). Having \( \theta_j \), the beaming-corrected energy can be calculated by \( E_{\gamma,j} = E_\gamma [1 - \cos(\theta_j)] \). We find that the beaming-corrected energy for GRB 160625B is extremely
high, up to $\sim 5.15 \times 10^{52} \text{ erg}$. Considering the error of $t_j$ and the uncertainties of $\eta$ and $n$ (the error of the fluence is less than 1% and need not to be considered), we estimate the lower and upper limits for $\theta_j$ and $E_{\gamma,j}$ by setting the parameter set $(t_j, \eta, n)$ in Equation (8) as $(1.3 \times 10^6, 0.1, 0.001)$ and $(2.3 \times 10^6, 0.9, 10)$, respectively. The $\theta_j$ and $E_{\gamma,j}$ with lower and upper limits (treated as errors) computed in this way are then $E_{\gamma,j} = 5.15^{+17.4}_{-4.29} \times 10^{52} \text{ erg}$ and $\theta_j = 0.106^{+0.116}_{-0.063} \text{ rad}$. To compare GRB 160625B with other bursts, we collect the samples from Tables 1 and 2 of Goldstein et al. (2016) and calculate their $E_{\gamma,j}$. For simplicity, we calculate the luminosity distance using the redshift, assuming a flat universe with $\Omega_M = 0.286$, $\Omega_\Lambda = 0.714$, and $H_0 = 69.6$ (Wright 2006), and take $\eta = 0.5$, $n = 0.1 \text{ cm}^{-3}$ for all of the bursts. We plot the $E_{\gamma,j}$ distribution of these bursts (blue bars) in Figure 4 and GRB 160625B (solid line), as well as its lower and upper limits (red dashed lines). We can find from Figure 4 that the $E_{\gamma,j}$ of GRB 160625B is higher than any of the previous bursts under the typical parameters.

Combining the Swift/XRT data with the observation from the optical and radio band collected from GCN, we also make an attempt to fit the multi-wavelength afterglow with the forward shock model, in which the Lorentz factor ($\Gamma$), the isotropic equivalent kinetic energy ($E_k$), the circumburst density ($n$), microphysical parameters ($\varepsilon_e, \varepsilon_b$), spectral index
of the electron energy distribution ($p$), as well as the half-opening angle ($\theta_j$) are taken as free parameters. We consider a homogeneous environment, and the revised fireball dynamics proposed by Huang et al. (1999) are used. With the code initially developed in Fan & Piran (2006), we find that the parameter set of $\Gamma = 200$ (which should be taken as an lower limit since we just fitted the data at $t \gtrsim 10^4$ s), $E_k = 6 \times 10^{53}$ erg, $n_c = 0.07$ cm$^{-3}$, $\epsilon_e = 0.3$, $\epsilon_b = 0.001$, $p = -2.1$, and $\theta_j = 0.135$ can reasonably reproduce the late time ($i.e., t > 10^4$ s) afterglow data, as shown in Figure 5. The half-opening angle and the circumburst density are consistent with what we assumed to derive the beaming-corrected energy noted previously (with this half-opening angle, $E_{\gamma,j} \approx 8 \times 10^{52}$ erg), and $E_k = 6 \times 10^{53}$ erg corresponds to an extremely high radiation efficiency of $\sim 94\%$. We note that due to the lack of a well-behaved rise of the afterglow, not all of the parameters can be well determined, especially the initial Lorentz factor. If what we obtained from the forward shock model (i.e., $\Gamma = 200$) is close to the real situation, the much lower bulk Lorentz factor comparing to the Lorentz factors of the unmerged shells can be explained by a great amount of kinetic energy of the fast shells being transferred into the radiation.

At last, the Pi of the Sky Telescope has detected a very bright optical flare accompanying GRB 160625B (Batsch et al. 2016). More efforts are needed to identify the origin of this flash (one possibility is that such a flash was triggered by the main GRB outflow ejected at $t \sim 186$ s catching up with the decelerated outflow material ejected at $t \sim 0$ s). If it was originated from the reverse shock of the outflow, the Lorentz factor can be measured in another way for GRB 160625B (Sari & Piran 1999; Wang et al. 2000; Fan et al. 2002; Soderber &
4. Conclusion
In the literature several methods have been proposed to estimate the Lorentz factors of the GRB outflow material. Some methods are only applicable to the whole burst (e.g., the methods based on the reverse shock optical flash modeling or the forward shock emission rise modeling), while some methods are valid for the time-resolved outflow material. The robustness of these estimates should be cross-checked. However, in reality such a goal is hard to achieve due to the limited data. In this work we show that GRB 160625B, an extremely bright long GRB with well-measured spectrum, provides us the valuable chance to do that. We perform spectral analysis on GRB 160625B, and find cutoffs and the evidence of thermal components in its time-resolved spectra. The cutoffs in GRB 160625B are unlikely caused by pair productions, since the Lorentz factors derived from the cutoffs are well below the lower limits set by the Compton scattering effect (see Figure 3). Instead these cutoffs may trace the spectra of accelerated electrons. The Lorentz factors derived from the thermal components within GRB 160625B follow the $\Gamma - L$ correlation with a slope of 0.40, which is nicely consistent with what holds for time-resolved distinct thermal components of GRB 090902B (Fan et al. 2012).

The consistency between the correlations found in GRB 160625B and GRB 090902B strengthens the presence of the distinct thermal components of GRB 090902B. The consistency between the correlations found in GRB 160625B and GRB 090902B is due to the limited data. In this work we show that GRB 160625B follow the $\Gamma - L$ correlation with a slope of 0.40, which is nicely consistent with what holds for time-resolved distinct thermal components of GRB 090902B (Fan et al. 2012).

We calculate the upper limits on the mass of the central black hole of GRB 160625B for different $Y$, and find that $Y$ should not be larger than $\sim 4$ in the first two time-intervals displaying thermal signature; otherwise the mass of the black hole will be lower than $2 M_\odot$, which has been ruled out by the latest neutron star mass measurement, in which the lower limit on the maximal gravitational mass is $2.01 \pm 0.04 M_\odot$ (Antoniadis et al. 2013). Interestingly, as shown in Figure 2, there might be evidence for the increases of the mass of the central black hole. Indeed the main outburst starting at $t \sim 186$ s may be due to the formation of a black hole. The extremely high geometry-corrected prompt gamma-ray energy $E_{\gamma} \sim 5 \times 10^{52}$ erg (or even $E_{\gamma} \sim 8 \times 10^{52}$ erg if we adopt the half-opening angle found in the numerical modeling of the late time afterglow; see Figure 5) is also in support of the black hole central engine, while a magnetar with a spin period $\lesssim 1$ ms and a typical moment of inertia $I \sim 2 \times 10^{45}$ g cm$^2$ makes it difficult to reproduce the data.

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