Extremely Bright GRB 160625B with Multiple Emission Episodes: Evidence for Long-term Ejecta Evolution

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Abstract

GRB 160625B is an extremely bright GRB with three distinct emission episodes. By analyzing its data observed with the Gamma-Ray Burst Monitor (GBM) and Large Area Telescope (LAT) on board the Fermi mission, we find that a multicolor blackbody (mBB) model can be used to fit very well the spectra of the initial short episode (Episode I) within the hypothesis of photosphere emission of a fireball model. The time-resolved spectra of its main episode (Episode II), which was detected with both GBM and LAT after a long quiescent stage (∼180 s) following the initial episode, can be fitted with a model comprising an mBB component plus a cutoff power-law (CPL) component. This GRB was detected again in the GBM and LAT bands with a long extended emission (Episode III) after a quiescent period of ∼300 s. The spectrum of Episode III is adequately fitted with CPL plus single power-law models, and no mBB component is required. These features may imply that the emission of the three episodes are dominated by distinct physics processes, i.e., Episode I is possible from the cocoon emission surrounding the relativistic jet, Episode II may be from photosphere emission and internal shock of the relativistic jet, and Episode III is contributed by internal and external shocks of the relativistic jet. On the other hand, both X-ray and optical afterglows are consistent with the standard external shocks model.

Key words: gamma-ray burst: individual (160625B)

1. Introduction

Long duration gamma-ray bursts (GRBs) are thought to be caused by the core-collapse of a massive star (Woosley 1993; Paczyński 1998); this is supported by several lines of observational evidence: (1) a handful of long GRBs are associated with SNe Ic (Galama et al. 1998; Stanek et al. 2003; Woosley & Bloom 2006), and (2) the host galaxies of long GRBs are in intense star-forming galaxies (Fruchter et al. 2006). Following the collapse, a black hole or magnetar central engine that powers an ultrarelativistic jet is formed (Usov 1992; Thompson 1994; Dai & Lu 1998; Popham et al. 1999; Narayan et al. 2001; Lei et al. 2013; Lü & Zhang 2014).

Numerical simulations show that a relativistic jet can be launched successfully, and it breaks out of the stellar envelope of the progenitor star (Zhang et al. 2003; Morsony et al. 2007; Mizuta & Ioka 2013; Geng et al. 2016). On the other hand, if the mass density of the collimated outflow is less than that of the stellar envelope, a “cocoon” component is the inevitable product when the jet propagates within the stellar envelope (Ramirez-Ruiz et al. 2002; Lazzati & Begelman 2010; Nakar & Piran 2017). The wasted energy of the jet is recycled into a high-pressure cocoon surrounding the relativistic jet (Ramirez-Ruiz et al. 2002; Lazzati & Begelman 2005). The energy that the cocoon gains is comparable to the energy released by the observed GRBs. Thus, the emission from the cocoon has been invoked as an explanation for the thermal emission of GRBs (Ghisellini et al. 2007; Piro et al. 2014) or for the precursor’s emission and steep decay in the early X-ray afterglow of GRBs (Ramirez-Ruiz et al. 2002; Pe’er et al. 2006; Lazzati et al. 2010). Ramirez-Ruiz et al. (2002) proposed that, theoretically, γ-ray and X-ray transients with a short duration may be produced by the cocoon emission. Lazzati et al. (2010) suggested that the transients may be seen as similar to a short GRB by an observer at wide angles. Nakar & Piran (2017) proposed that possible signatures (γ-ray, X-ray, and optical) of the cocoon emission may be detected, but it is strongly dependent on the level of mixing between the shocked jet cocoon and the shocked stellar cocoon. In any case, the cocoon emission is also expected to have a thermal component in the observed spectrum in the above models (Ramirez-Ruiz et al. 2002; Lazzati & Begelman 2005).

After the jet breaks out of the stellar envelope, the outflow of the relativistic jet produces prompt γ-ray emission, which passes through internal shocks or undergoes magnetic dissipation, becoming optically thin (Meszaros & Rees 1993; Piran et al. 1993; Rees & Meszaros 1994; Zhang & Yan 2011). Within the matter-dominated fireball scenario, it was expected that the observed GRB spectrum should be composed of a thermal component from the photosphere emission and a non-thermal component from the synchrotron radiation of relativistic electrons in the internal shock regions (Mészáros & Rees 2000; Rees & Mészáros 2005; Pe’er et al. 2006; Giannios 2008; Beloborodov 2010; Lazzati & Begelman 2010). Therefore, a bright blackbody component should be detectable. After that, a multiwavelength afterglow emission is produced when the fireball (outflow) propagates into the surrounding medium (Mészáros & Rees 1997; Sari et al. 1998; Zhang & Kobayashi 2005; Fan & Piran 2006; Gao et al. 2013).

From an observational point of view, only 10% GRBs have a precursor emission component, and the spectral properties of precursors and main outbursts do not show any statistical differences (Troja et al. 2010; Hu et al. 2014). On the other hand, GRBs with precursors are not substantially different from GRBs without precursors (Troja et al. 2010; Hu et al. 2014).
These results suggest that the precursor would be the same emission component as the fireball.

Recently, an extremely bright GRB, 160625B, was detected by the Fermi Gamma-Ray Burst Monitor (GBM) and Large Area Telescope (LAT), with a measured redshift \( z = 1.406 \) (Xu et al. 2016). Its prompt \( \gamma \)-ray light curve is composed of three episodes: a short precursor, a very bright main emission episode, and a weak emission episode. The three episodes of emission are separated by two long quiescent intervals (Zhang et al. 2016b). Interestingly, Zhang et al. (2016b) found that a purely thermal spectral component and a non-thermal spectrum (known as a Band function; Band et al. 1993) existed in the precursor and main emission episodes, respectively. They suggested that the thermal component is from the photosphere emission of a fireball, and the non-thermal component is from a Poynting-flux-dominated outflow (see also Fraija et al. 2017). However, it is inconceivable that the transition from a fireball-to Poynting-flux-dominated jet lasts that long in the quiescent stage. In this paper, by re-analyzing the multiwavelength data of GRB 160625B, we propose that the precursor and main emission may originate from different physics processes, i.e., cocoon emission surrounding the jet and relativistic jet. Then, we also explore the long-term evolution of the ejecta.

This paper is organized as follows: the data reduction and data analysis are presented in Sections 2 and 3. In Section 4, we derive the ejecta properties from the data. Conclusions and discussion are reported in Sections 5 and 6. We adopt the convention \( F_{\nu}(t) \propto t^{-\alpha} \nu^{\beta} \) throughout this paper.

## 2. Data Reduction

GRB 160625B triggered the Fermi/GBM at 22:40:16.28 UT on 2016 June 25 (\( T_0 \)) for the first time (Burns 2016). This GRB was also detected by Konus/Wind (Svinkin et al. 2016). It is the brightest event observed by Konus/Wind in its more than 21 years of GRB observations (Svinkin et al. 2016). Interestingly, the Fermi/LAT was also triggered by this burst at \( T_0 + 12.85 \text{ s} \) (Dirirsa et al. 2016), and more than 300 photons with energy above 100 MeV were detected. The highest photon energy is about 15 GeV (Dirirsa et al. 2016; Zhang et al. 2016b). This GRB triggered the GBM again at \( T_0 + 660 \text{ s} \).

We download the GBM and LAT data of GRB 160625B from the public science support center at the official Fermi Web site.\(^3\) The GBM has 12 sodium iodide (NaI) detectors covering an energy range from 8 keV to 1 MeV, and two bismuth germanate (BGO) scintillation detectors sensitive to higher energies between 200 keV and 40 MeV (Meegan et al. 2009). We select the brightest NaI and BGO detectors for the analyses. The spectra of this source are extracted from the TTE data, and the background spectra of the GBM data are extracted from the CSPEC format data with user-defined intervals before and after the prompt emission phase. We reduce the LAT data using the LAT ScienceTools-v9r27p1 package and the P7TRANSIENT V6 response function (detailed information for the LAT GRB analysis are available in the NASA Fermi Web site). Two types of LAT data are available, the LAT Low Energy (LLE) data in the 20 MeV–100 GeV band and the high-energy LAT data in the 100 MeV–300 GeV band. We extract the light curves and spectra of GRB 160625B from the GBM and LAT data.

Follow-up observation with the X-ray telescope (XRT) on board Swift was performed between \( T_0 + 9.6 \text{ ks} \) and \( T_0 + 10.0 \text{ ks} \) (Melandri et al. 2016). The Swift/XRT light curve and spectrum are extracted from the UK Swift Science Data Center at the University of Leicester.\(^4\) A bright optical flare at the main prompt gamma-ray episode was detected with the Mini-Mega TORTORA nine-channel wide-field monitoring system and other optical telescopes. We collect the optical data from Zhang et al. (2016b).

## 3. Data Analysis

### 3.1. Prompt Emission

Figure 1 shows the light curves of the prompt and very early optical afterglow emission of GRB 160625B. The GBM-NaI light curve has three distinct episodes with 1 s time bins. The first episode lasts about one second (Episode I). The inset in the top panel of Figure 1 shows the light curve in the 64 ms time bin. One finds that it is a single pulse that is rapidly rising and decaying. It was not detected with GBM-BGO and LAT. The source was in a quiescent stage with a duration of about 180 s wherein no gamma-rays in the GBM and LAT bands were detected. An extremely bright gamma-ray outburst with multiple peaks (Episode II) triggered Fermi/LAT and was also observed with GBM; it had been in the optical band since \( T_0 + 187 \text{ s} \). The source was in quiescent again and triggered the GBM at \( T_0 + 520 \text{ s} \). The emission in this episode (Episode III) was detected with the GBM-NaI detector and LAT. The light curve of this episode features a long-lasting, low flux-level episode, similar to the extended emission (EE) component (e.g., Hu et al. 2014). Its duration is 372 s. Therefore, GRB 160625B experienced a short precursor, a main burst, and a long-lasting extended emission stage. The initial three data points of the V-band light curve of the optical flare observed during Episode II with the Mini-Mega TORTORA system is

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\(^3\) http://fermi.gsfc.nasa.gov/ssc/data/

\(^4\) http://www.swift.ac.uk/xrt_curves/00020667/
analyze the spectra observed with different detectors/telescopes for the first emission episode of the prompt gamma-rays. Figure 2 shows the observed count spectrum and $v_f$, of Episode I in the GBM energy band. We find that the mBB model is adequate to fit the spectrum of this episode. One obtains $kT_{\text{max}} = 25.2 \pm 1.1$ keV, $kT_{\text{min}} = 3.45 \pm 1.26$ keV, and $q = 0.63 \pm 0.2$. For Episode II, a Band function is also proposed to fit the spectra without considering LAT data (Zhang et al. 2016b; Wang et al. 2017). In this paper, we use the empirical multicolor blackbody (which motivated by the standard fireball model) plus CPL model to do the time-resolved spectral fit (see Tables 1 and Figure 3) and get a better goodness of fit. In order to test whether other models can be used to fit the data, we invoke either an mBB, mBB plus power-law (e.g., GRB 090902B, Ryde et al. 2010), or Band function models to do the spectral fit. We find that the PGSTAT/dof of the mBB or the mBB plus power-law model is too large to be adopted (PGSTAT/dof $> 2$), but the Band function is likely to fit the data very well in some time interval. In order to compare the Band function fitting and mBB plus CPL model fitting of Episode II, we give the count and $v_f$ spectrum for all time-resolved spectra (14 time slices). Figure 4 shows one example of a time slice ($[191 \sim 192]$ s) for the count and $v_f$ spectrum of those two models. Figure 5 shows the comparison photon models between Band and mBB with CPL. On the other hand, in Figure 6, we compare the goodness of the Band function fitting with the mBB+CPL fitting, and presents the PGSTAT/dof and Bayesian information criterion (BIC) as a function of time for each time slice. From a statistical point of view, the mBB+CPL model and Band function are comparable with each other.

By invoking the mBB+CPL model to fit the spectra of Episode II, we find that the mBB component dominates the emission in the range from tens to hundreds of keV, and the emission in both the several keV and MeV range are attributed to the CPL component. $kT_{\text{max}}$ initially rapidly increases with time from 643 ± 67 keV to 1096 ± 23 keV, then gradually decays to 250–350 keV. The power-law index $q$ varies from 0.60 to 1.05. For the CPL

\[ q \text{ varies from 0.60 to 1.05.} \]

The Bayesian information criterion is a criterion for model selection among a finite set of models. The model with the lowest BIC is preferred. The BIC can be written as $\text{BIC} = \chi^2 + k \cdot \ln(n)$, where $k$ is the number of model parameters and $n$ is the number of data points. The strength of the evidence against the model with the higher BIC value can be summarized as follows. (1) If $0 < \Delta \text{BIC} < 2$, the evidence against the higher BIC is not worth more than a mere mention; (2) if $2 < \Delta \text{BIC} < 6$, the evidence against the higher BIC is positive; (3) if $6 < \Delta \text{BIC} < 10$, the evidence against the higher BIC is strong; (4) if $10 < \Delta \text{BIC}$, the evidence against the higher BIC is very strong.

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\[ F_{\text{mBB}}(E, T) = \int_{T_{\text{min}}}^{T_{\text{max}}} dA(T) \frac{E^3}{dT} \exp\left[\frac{E}{kT}\right] - 1 \, dT, \]

where $T_{\text{max}}$ and $T_{\text{min}}$ are free parameters, and $F(T) = \frac{q^3}{E^4}A(T)T^4$, where $A(T)$ is the normalization. We assume that the flux of the thermal component is the power-law distribution with the temperature, which reads

\[ F(T) = F_{\text{max}} \left( \frac{T}{T_{\text{max}}} \right)^q, \]

and $q$ measures the power-law distribution of the temperature. We describe the non-thermal emission component with a cutoff power-law (CPL) model, i.e., $F_{\text{non-d}} = F_{\text{c}}E^{-\gamma}e^{-E/E_{\gamma}}$.

We perform the spectral fit with the Xspec package and evaluate the goodness of our fits with the maximum likelihood-based statistics, the so-called PGSTAT (Cash 1979). We jointly

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\[ T_{\text{max}} \text{ initially rapidly increases with time from 643 ± 67 keV to 1096 ± 23 keV, then gradually decays to 250–350 keV.} \]
Figure 3. Observed time-resolved $\nu F_{\nu}$ spectra of the Episode II emission (the main emission episode) together with our fits with the mBB+CPL model (dot lines). The black points, red points, and green points are the data observed with NaI, BGO, and LAT, respectively.
component, we do not find any clear temporal evolution feature of $\Gamma_\nu$, which is in the ranges $\Gamma_\nu \in (1.27, 1.69)$. Figure 7 shows the temporal evolution of $kT_{\text{max}}$, $kT_{\text{min}}$, and $E_c$. Note that the bright optical flare was simultaneously detected in Episode II. It peaks at $T_\text{0} + \sim 200 \text{ s}$ with an exposure time of 10 s. We show the model curves derived from our fit for the spectrum observed in the time slice $[195-205]\text{ s}$ in comparison with the peak optical flux in Figure 8. Here, the optical data are corrected for the extinction by the Milky Way Galaxy ($A_V = 0.349$), but are not corrected for the extinction by the GRB host galaxy due to the uncertain extinction curves. It is found that the optical flux is higher than the model result by a factor of 3. Therefore, the flux may be contributed by both prompt optical emission and the reverse shocks, as we will discuss below.

Although the duration of Episode III is longer than that of Episode II, its lower flux cannot be used to perform the time-resolved analysis for this episode. Hence, one derives the time-integrated spectrum of Episode III, which is shown in Figure 9. It is found that the emission in the LAT energy band is dominated by an extra power-law (PL) component. The spectrum cannot be fitted with the mBB+CPL model. Therefore, we use a CPL plus a single PL model to fit the data. One obtains $\Gamma_\nu = 1.64 \pm 0.05$, $E_c = 0.69 \pm 0.58 \text{ GeV}$, and the index of the single PL component is $1.98 \pm 0.5$.

### 3.2. Late Afterglows

Both optical and X-ray afterglows were detected with XRT and UVOT on board *Swift* and ground-based telescopes from...
| Time interval  | $kT_{\text{min}}$ (keV) | $kT_{\text{max}}$ (keV) | $q$ | $\Gamma_0$ | $E_0$ (MeV) | $\dot{\nu}$ | $\dot{E}_p$ (keV) | PGS/dof | ΔBIC | BIC-selected Model |
|----------------|-------------------------|-------------------------|-----|-----------|-------------|-----------|----------------|---------|------|------------------|
| [180 ~ 187]   | 15.1 ± 1.20             | 643 ± 88                | 0.90 ± 0.04 | 1.27 ± 0.02 | 12.11 ± 0.83 | −0.89 ± 0.02 | −4.22 ± 0.51 | 310/271 | −54 | Band(very strong) |
| [187 ~ 188]   | 30.0 ± 0.26             | 871 ± 57                | 0.81 ± 0.03 | 1.31 ± 0.02 | 17.19 ± 3.40 | −0.96 ± 0.03 | −2.85 ± 0.11 | 276/273 | 47  | mBB+CPL(very strong) |
| [188 ~ 189]   | 32.0 ± 0.38             | 1096 ± 22               | 0.64 ± 0.02 | 1.34 ± 0.02 | 16.59 ± 1.03 | −0.77 ± 0.02 | −2.64 ± 0.03 | 369/274 | 541 | mBB+CPL(very strong) |
| [189 ~ 190]   | 25.0 ± 0.48             | 940 ± 20                | 0.60 ± 0.02 | 1.50 ± 0.03 | 23.0 ± 3.65  | −0.75 ± 0.03 | −2.62 ± 0.02 | 362/270 | 546 | mBB+CPL(very strong) |
| [190 ~ 191]   | 17.0 ± 0.29             | 659 ± 7                 | 0.59 ± 0.02 | 1.60 ± 0.02 | 26.97 ± 1.40 | −0.81 ± 0.03 | −2.58 ± 0.04 | 318/271 | 354 | mBB+CPL(very strong) |
| [191 ~ 192]   | 7.0 ± 0.69              | 260 ± 35                | 0.68 ± 0.03 | 1.52 ± 0.02 | 8.75 ± 0.90  | −0.81 ± 0.05 | −2.70 ± 0.07 | 299/254 | 300 | Band(very strong)   |
| [192 ~ 193]   | 5.0 ± 0.73              | 254 ± 34                | 0.72 ± 0.03 | 1.47 ± 0.03 | 7.64 ± 0.44  | −0.81 ± 0.05 | −2.70 ± 0.08 | 305/278 | 307 | Band(very strong)   |
| [193 ~ 194]   | 13.0 ± 2.09             | 289 ± 38                | 0.92 ± 0.04 | 1.50 ± 0.01 | 10.35 ± 0.96 | −0.70 ± 0.04 | −2.78 ± 0.06 | 296/276 | 416 | Band(very strong)   |
| [194 ~ 195]   | 12.0 ± 1.62             | 350 ± 37                | 0.86 ± 0.03 | 1.53 ± 0.08 | 12.07 ± 0.91 | −0.74 ± 0.03 | −2.80 ± 0.05 | 315/275 | 390 | Band(very strong)   |
| [195 ~ 196]   | 10.0 ± 1.57             | 287 ± 36                | 1.02 ± 0.02 | 1.38 ± 0.03 | 7.60 ± 0.49  | −0.72 ± 0.03 | −2.88 ± 0.07 | 307/275 | 295 | Band(very strong)   |
| [196 ~ 197]   | 9.0 ± 0.84              | 252 ± 32                | 1.01 ± 0.03 | 1.40 ± 0.02 | 7.79 ± 0.45  | −0.74 ± 0.04 | −2.89 ± 0.08 | 362/275 | 362 | Band(very strong)   |
| [197 ~ 198]   | 7.1 ± 1.43              | 338 ± 27                | 0.94 ± 0.04 | 1.69 ± 0.08 | 53.48 ± 2.69 | −0.78 ± 0.03 | −3.08 ± 0.10 | 287/272 | 310 | mBB+CPL(very strong) |
| [198 ~ 199]   | 10.0 ± 2.14             | 292 ± 52                | 0.98 ± 0.04 | 1.54 ± 0.05 | 16.11 ± 4.18 | −0.78 ± 0.03 | −2.71 ± 0.05 | 283/275 | 316 | mBB+CPL(very strong) |
| [199 ~ 200]   | 8.1 ± 1.63              | 338 ± 24                | 1.05 ± 0.06 | 1.51 ± 0.09 | 10.44 ± 1.16 | −0.75 ± 0.03 | −3.02 ± 0.08 | 250/275 | 263 | mBB+CPL(very strong) |

**Note.**

The $E_p$ for the first three time slices is much higher than that for the other time slices. The reason may be due to fewer LLE photons contributing or spectral evolution within more time slices that are smaller, and the $E_p$, not able to reflect the intrinsic spectral properties.
Their light curves show similar features (Figure 10). The later optical afterglow light curve can be well-fitted with a smooth broken power-law function, $F = F_0 \left[ \left( \frac{t}{t_0} \right)^{\alpha_{O,1}} + \left( \frac{t}{t_0} \right)^{\alpha_{O,2}} \right]^{1/\omega}$, and we fixed $\omega = 1/3$, which describes the sharpness of the break (Liang et al. 2007).

The derived parameters are $\alpha_{O,1} = -0.92 \pm 0.04$, $\alpha_{O,2} = -2.30 \pm 0.51$, and $t_{O,b} = (2.33 \pm 0.40) \times 10^6$ s. The X-ray light curve can also be fitted with this function with the parameters $\alpha_{X,1} = -1.31 \pm 0.02$, $\alpha_{X,2} = -2.38 \pm 0.75$, and $t_{X,b} = 2.33 \times 10^6$ s (fixed). The achromatic breaks could be due to the jet effect (Rhoads 1997).

We jointly fit the afterglow spectra in the optical–X-ray bands in the four selected time slices as marked in Figure 10. By correcting the extinction for the optical data and fixing the neutral hydrogen absorption for the soft X-rays of our Galaxy to $N_H = 9.76 \times 10^{20}$ cm$^{-2}$, we find that a single power-law function is adequate to fit the spectra, yielding photon indices $\Gamma = -1.72 \pm 0.02$, $-1.70 \pm 0.02$, $-1.76 \pm 0.04$, and $-1.85 \pm 0.03$ for the spectra derived from the four selected time slices. The extinction of the GRB host galaxy is negligible in our fits. Our results are shown in Figure 11. The observed flux slope and the photon index are roughly satisfied with the closure relation $\alpha \sim 3\beta/2$, where $\beta = \Gamma - 1$. This suggests that both the X-ray and optical aftergloows should be in the spectral regime of $\nu_m < \nu < \nu_c$, where $\nu_m$ and $\nu_c$ are the characteristic frequencies of the synchrotron radiation of the relativistic electrons.

4. Derivation of the Ejecta Properties within the Fireball Models

4.1. Lorentz Factor and Radius of the GRB Photosphere

Zhang et al. (2016b) proposed that the jet composition is fireball- to Poynting-flux dominated, and linear polarization...
Figure 6. Comparison of the statistical difference between PGSTST/dof (left) and BIC (right) using the mBB+CPL model of Episode II with the Band function for each time interval.

Figure 7. Temporal evolution of $T_{\text{min}}$, $T_{\text{max}}$, $E_c$, and $p_h$ during Episode II. The top panel shows the light curves of GBM/NaI and LAT.

Figure 8. Model curves derived from our fit to the spectrum observed in the time slice [195–205] s in comparison with the peak optical flux (the blue dashed line) in the same time interval, where the optical data are corrected for the extinction by the Milky Way galaxy and by removing the contribution of the reverse shock at this time, but they are not corrected for the extinction by the GRB host galaxy.

Figure 9. Time-integrated spectrum of the Episode III emission together with our fit using the CPL+PL model (solid line).

Figure 10. Light curves of the prompt optical, early, and later optical afterglow, and the X-ray afterglow of GRB 160625B. The red line is our model fit with the external shock model, in which the reverse shock and forward shock emission components are represented by the dashed–dotted–dotted and dashed–dotted lines, respectively. The extremely sharp optical pulse of the first three optical data points suggest that they are dominated by the prompt optical flare (black dotted lines). The vertical dashed lines denote the selected time slices of our spectral analysis.
during the prompt emission was detected (Troja et al. 2017). In our analyses, the time-resolved spectra of Episode II comprises two parts: one is a thermal component, and the other is a non-thermal component (the CPL component). The observed polarization may be contributed by the non-thermal component. On the other hand, we assume that the mBB component is from the contributions of the photosphere emission. Then, we estimate the $R_{\text{ph}}$ values and radius of the GRB photosphere with the mBB component derived from our spectral fits in different emission episodes. We estimate the $\Gamma_{\text{ph}}$ of photosphere emission following Pe'er et al. (2007),

$$\Gamma_{\text{ph}} = \left[ \frac{1.16}{\left(1 + z\right)^2} D_L \frac{Y \sigma_T F_{\text{obs}}}{2m_p c^2 \sigma T} \right]^{1/4} ,$$

where $D_L$ is the luminosity distance, $m_p$ is the proton mass, $\sigma_T$ is the Thomson scattering cross-section, $Y$ is the ratio between the total fireball energy and energy radiated in the $\gamma$-ray band, which is fixed at $Y = 1$ in our calculation, and $F_{\text{obs}}$ is the total observed flux of both the thermal ($F_{\text{mBB}}$) and non-thermal ($F_{\text{non-BB}}$) components. $\sigma T$ is defined as

$$\sigma T = \left( \frac{F_{\text{obs}}}{T_F^4} \right)^{1/2} ,$$

where $F_{\text{obs}}$ is the observed total flux of the mBB component and $\sigma$ is Stefan’s constant. The radius of the photosphere can be estimated via

$$R_{\text{ph}} = \frac{\sigma T L_0 D_L^3}{8 \pi m_p c^3 (1 + z)^6 \left( \frac{F_{\text{obs}}}{T_F^4} \right)^{3/2}} \left( \frac{\sigma T}{\sigma T_{\text{max}}} \right)^{3/4} ,$$

where $L_0$ is a total luminosity of both the thermal and non-thermal emission.

The derived $\Gamma_{\text{ph}}$ and $R_{\text{ph}}$ values are reported in Table 2. The $\Gamma_{\text{ph}}$ value in Episode I is found to be 175. During Episode II, initially, the $\Gamma_{\text{ph}}$ is 1162 in the time slice of [180–187] s. Then, it rapidly goes up to 2274 at the time slice of [188–189] s, and goes down and remains at about 800–1100 in the later time slices. The $R_{\text{ph}}$ value increases from $1.52 \times 10^{10}$ cm to $2.66 \times 10^{11}$ cm, then remains in the range of $(2.66 - 3.76) \times 10^{11}$ cm. The temporal evolution of the $\Gamma_{\text{ph}}$ and $R_{\text{ph}}$ values are shown in the bottom panel of Figure 7. The extremely large Lorentz factor may make this event extremely bright (e.g., Liang et al. 2010; Wu et al. 2011).

### Notes

- The observed total flux of the mBB component and non-thermal component, respectively. The flux is in units of $10^{-5}$ erg cm$^{-2}$ s$^{-1}$.
- The Lorentz factor of the GRB photosphere.
- The radius of the photosphere in units of $10^{11}$ cm.

### Table 2

| Time Interval(s) | $F_{\text{obs}}$ | $F_{\text{obs}}$ \cite{non-BB} | $\Gamma_{\text{ph}}$ | $R_{\text{ph}}$
|------------------|-----------------|--------------------------|-----------------|----------------|
| [180 ~ 187]     | 0.11            | 0.22                      | 1162             | 0.15            |
| [187 ~ 188]     | 1.54            | 2.41                      | 1798             | 0.50            |
| [188 ~ 189]     | 8.98            | 6.42                      | 2274             | 0.96            |
| [189 ~ 190]     | 10.11           | 4.19                      | 2035             | 1.24            |
| [190 ~ 191]     | 4.64            | 1.81                      | 1540             | 1.29            |
| [191 ~ 192]     | 1.45            | 0.99                      | 878              | 2.66            |
| [192 ~ 193]     | 1.43            | 1.13                      | 879              | 2.78            |
| [193 ~ 194]     | 2.57            | 1.19                      | 959              | 3.13            |
| [194 ~ 195]     | 3.57            | 1.55                      | 1095             | 2.87            |
| [195 ~ 196]     | 3.37            | 1.62                      | 992              | 3.76            |
| [196 ~ 197]     | 2.49            | 1.01                      | 883              | 3.74            |
| [197 ~ 198]     | 2.93            | 0.20                      | 975              | 2.48            |
| [198 ~ 199]     | 2.47            | 1.05                      | 953              | 2.98            |
| [199 ~ 200]     | 3.39            | 0.76                      | 1028             | 2.81            |

Figure 11. Spectral energy distributions of the optical–X-ray emission in the four selected time intervals. Dashed lines are the spectral fitting with absorbed power-law functions that are extrapolated to the optical bands.

#### 4.2. Jet Properties Derived from the Afterglow Data

As mentioned in Section 3.2, the late afterglow data are consistent with the prediction of the standard afterglow models. We derive the jet properties from the afterglow data in this section. For details of our model and fitting strategy, please refer to Huang et al. (2016). With the observed spectral index and temporal decay slope of the normal decay segment (from $10^6$ to $10^8$ s), we suggest that both the optical and X-ray emission should be in the spectral regime between $\nu_0$ and $\nu_e$, and take $p = 2/3 + 1 \sim 2.4$, where we take $\beta \sim 0.70$ derived from the time slice $[1.5-2.0] \times 10^5$ s. The fractions of internal energy transferred to electrons and the magnetic field are $e_{e,r}$ and $e_{\text{B,r}}$, in the reverse shock region, and $e_{e,f}$ and $e_{\text{B,f}}$ in the forward shock region. We assume that the medium surrounding the jet is the interstellar medium (ISM) with a constant density ($n$). The temporal evolutions of both minimum and cooling frequencies ($\nu_m$ and $\nu_c$) in the reverse and forward shock regions are taken from Rossi & Rees (2003), Fan & Piran (2006), Zhang et al. (2007), and Yi et al. (2013). We use a Monte Carlo (MC) technique to make the best fit to the observed light curves (Huang et al. 2016; Xin et al. 2016) and derive the best parameter set that can reproduce the light curve of the observations. A probability $p_t = \exp(-\chi^2/2)$ was invoked to measure the goodness of our fits, where $\chi^2$ is the reduced $\chi^2$. Figure 12 shows the $p_t$ distributions along with our Gaussian fits for the best model parameters obtained with our MC technique, and the distributions of those parameters, e.g., $e_{e,r}, e_{e,f}, e_{\text{B,r}}$, the fireball kinetic energy $E_{\text{K,iso}}$, the initial fireball Lorentz factor $\Gamma_0$, and jet opening angle $\theta_j$ are well fit with a Gaussian function However, due to the contributions of the initial optical flare, $e_{\text{B,f}}$ and $n$ are not convergent and hence cannot be fit by a Gaussian function, so we fix those two parameters as $e_{\text{B,f}} \sim 4 \times 10^{-5}$ and $n \sim 36$ cm$^{-3}$. For other parameters, one obtains $e_{e,r} = 0.16 \pm 0.02$, $e_{e,f} =$...
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\[ \epsilon_{B,f} = (1.82 \pm 0.47) \times 10^{-7}, \quad E_{K,iso} = (1.72 \pm 0.12) \times 10^{55} \text{ erg}, \quad \Gamma_0 = 116 \pm 4, \quad \text{and} \quad \theta_j = 12^\circ \pm 2^\circ. \]

Defining a magnetization parameter as \( R_B \equiv \frac{\epsilon_{B,f}}{\epsilon_{B,1}}, \) one obtains \( R_B \sim 222. \) It is lower than that of GRBs 990123, 090102, 130427A, and 140512A, whose early optical emission are dominated by the reverse shock emission. Late optical and X-ray afterglows since the time interval are dominated by the reverse emission. The segment with a decaying slope of \(-3.57 \pm 0.09\) is dominated by the reverse shock emission. Late optical and X-ray afterglows since \( t > 10^4 \text{ s} \) are contributed by the forward shock emission.

5. Discussion

The three well-separated emission episodes observed in GRB 160625B have distinct spectral properties. This may shed light on the evolution of the outflow and even the activity of the GRB central engine. In this section, we discuss the possible physical origins of these distinct emission episodes and implications for the central engine of GRB 160625B.

5.1. Episode I: Emission of the Cocoon Surrounding the Jet?

Episode I is a short precursor followed by a long quiescent stage. Hu et al. (2014) analyzed a large sample of GRB light curves observed with the Swift Burst Alert Telescope (BAT) in order to search for a possible precursor emission prior to the main outbursts. They found that about 10% of long GRBs have a precursor emission component. Most of the precursors show up as continuous fluctuations with a low flux level. Due to the narrowness of the BAT band, they fitted the spectra of both the precursors and the main outbursts. They found that their photon indices do not show any statistical difference and suggested that the precursor is the same emission component from the fireball (see also Lazzati 2005; Burlon et al. 2008). The Episode I emission of GRB 160625B is dramatically different from these precursors. Its spectrum is well-fitted by an mBB model. In addition, it is very short and bright. Figure 13(a) compares Episode I of GRB 160625B with the precursors of some Swift GRBs in the plane of the hardness ratio (HR) versus the duration of the precursors \( T_{\text{pre}} \), where HR is the ratio of the photon fluxes between the 50–100 keV and 15–150 keV bands. It is found that the emission of Episode I is significantly harder than that of the Swift GRBs. The peak fluxes of the precursors of these Swift GRBs are also tightly correlated with those of the main outbursts, but the emission in Episode I deviates from this correlation, as shown in Figure 13(b). The peak flux of Episode I of GRB 160625B is much brighter than other Swift GRBs. After the end of Episode I, no signal was detected by GBM and LAT until Episode II begins. Although the tail emission of Episode I may be detectable with Swift/XRT as usually seen in some GRBs (e.g., Peng et al. 2014), the rapid end of this episode and the long quiescent stage may indicate the rapid close of this emission channel. Therefore, the physical origin of the emission in Episode I may hold the key to revealing the evolution of the GRB jet.

Several models were proposed to interpret the precursor emission of GRBs (Lyutikov & Usov 2000; Ramirez-Ruiz et al. 2002; Wang & Mészáros 2007; Bernardini et al. 2013). It is believed that long GRBs are relativistic fireballs from the collapse of massive stars. Lyutikov & Usov (2000) suggested that a weak precursor may be attributed to the photosphere emission of the GRB fireball when it becomes transparent. In this scenario, the spectrum of the precursor should be thermal or quasi-thermal. Our spectral analysis indicates that the spectrum of the Episode I emission can indeed be fitted with the mBB model. In this scenario, our results likely suggest that the GRB fireball experienced an acceleration stage from Episode I to Episode II when the fireball expanded. However,
the short duration of Episode I and the long quiescent stage after it are difficult to explain with this scenario since the photosphere emission could not be rapidly shut down when the fireball is transparent.

Ramirez-Ruiz et al. (2002) suggested that a cocoon surrounding a relativistic jet may be formed when the jet breaks out of the progenitor envelope. They assumed that the cocoon has the same Lorentz factor as the GRB jet and discussed possible photospheric “cooling emission” from the cocoon. This emission component may produce gamma-ray and X-ray transients with a short duration since this channel should rapidly close due to the drop of pressure. Lazzati et al. (2010) investigated the cocoon evolution and suggested that the transients may be seen to be similar to a short GRB by an observer at 45°. More recently, Nakar & Piran (2017) explored the possible signatures of the cocoon emission. They showed that the cocoon signature depends strongly on the level of mixing between the shocked jet and shocked stellar material. In the case where there is no mixing, bright gamma-ray emission with a duration of seconds from the cocoon can be detectable with current missions, such as Swift and Fermi. The non-detection of such an emission component in most GRBs indicates that such kind of mixing must take place. The spectrum and duration of the emission in Episode I of GRB 160625B seem to be consistent with the case of no mixing at all. This makes this GRB very valuable for revealing the progenitor and jet of this GRB (Nakar & Piran 2017).

5.2. Episode II: Main Burst from the Jet?

Our time-resolved spectral analysis for the emission in Episode II shows that the spectra are well-fitted with the mBB + CPL model. J. Lü et al. (2017, in preparation) present a systematic spectral fit for 37 bright GRBs simultaneously observed by GBM and LAT by invoking the mBB+PL or mBB+PL model. They showed that the spectra of 32 GRBs can be fitted with the mBB+PL model, and the spectra of the remaining five GRBs are adequately fitted with the mBB+PL model. Therefore, the gamma-ray emission of Episode II should resemble that of typical LAT GRBs.

A bright optical flare was simultaneously detected in Episode II. Based on our theoretical modeling with the forward and reverse shock models for the optical and X-ray data as shown in Figure 8, one finds that this flare is shaped by both the prompt optical emission and reverse shock emission, similar to that observed in GRB 140512A (Huang et al. 2016). By subtracting the contribution of the reversed shock emission, the optical flux at the peak time is scaled down a little bit to that extrapolated from the fitting result of the gamma-ray emission.8

With the isotropic kinetic energy derived from our modeling for the afterglow data and the observed gamma-ray energy of Episode II, we also calculate the GRB radiation efficiency with $\eta = E_{\gamma,iso}/(E_{\gamma,iso} + E_{iso})$ and obtain $\eta = 14.9 \pm 0.9 \%$. We compare the radiation efficiency of GRB 160625B with that of other GRBs (Racusin et al. 2011). It is also similar to typical long GRBs, as shown in Figure 14.

8 This situation may be caused by two possible reasons. One reason may be the uncertainty extrapolated from the $\gamma$-ray to the optical band. Another reason may be the different radiation mechanisms between the $\gamma$-ray and optical emission.
5.3. Episode III: Extended Emission and High-energy Afterglow Emission?

From Figure 1, one can observe that the emission of this episode is clearly detected with GBM-NaI and LAT. The light curve observed with NaI features the extended emission seen in most GRBs (Hu et al. 2014), but the LAT light curve of this episode shows a steady increase right after the end of Episode II. The spectrum of Episode III is shown in Figure 9, which also suggests that they should be different emission components. The spectrum observed with LAT should be a distinct spectral component from the spectrum observed with GBM. It is well fit with a single power-law with an index of 1.98 ± 0.5. This component is similar to the extra power-law component observed in GRBs 090902B and 990510 (Ryde et al. 2010; Zhang et al. 2011). We suspect that this component is the high-energy afterglows produced in the forward region and the steady increase of the LAT flux could be the onset of the high-energy afterglows (e.g., Ghisellini et al. 2010).

6. Conclusions

GRB 160625B is an extremely bright GRB with measured redshift $z = 1.406$. The light curve of the prompt emission is composed of three distinct episodes: a short precursor (Episode I), a very bright main emission episode (Episode II), and a weak emission episode (Episode III). These three emission episodes are separated by two quiet periods of $\sim 180$ and $\sim 300$ s, respectively. The total isotropic-equivalent energy ($E_{\text{iso}}$) and peak luminosity ($L_{\text{iso}}$) are as high as $\sim 3 \times 10^{54}$ erg and $\sim 4 \times 10^{53}$ erg s$^{-1}$, respectively. The early optical emission is very bright, with 8.04 mag during the main emission episode. By analyzing the data observed with the GBM and LAT on board the Fermi mission, we find the following interesting results:

1. The emission of Episode I is significantly harder than that of the Swift GRBs. The spectrum of Episode I can be fitted with a mBB model, and the derived maximum temperature ($kT_{\text{max}}$) is $\sim 25$ keV. These features suggest that Episode I is different from other detected Swift GRB precursors. We propose that the emission of Episode I seems to be from the emission of the cocoon surrounding the jet where there is no mixing between the shocked jet cocoon and shocked stellar cocoon.

2. The extremely bright emission of Episode II has a higher isotropic-equivalent energy, and the time-resolved spectral analysis for the emission of Episode II shows that the spectra are well-fitted with a model composed of an mBB component plus a CPL component. The radiation efficiency of this episode is similar to that of other typical long GRBs. These features suggest that the emission of Episode II is contributed by both photosphere emission and the internal shock of the relativistic jet. However, the Poynting-flux-dominated outflow cannot be ruled out only based on the data.

3. The spectrum of Episode III is adequately fitted with a CPL plus a single power-law model, and no mBB component is required. This may imply that the emission of Episode III is contributed by both internal and external shocks of the relativistic jet.

4. The early and later afterglows are consistent with the reverse and forward shock models, respectively. We derived an initial fireball Lorentz factor $\Gamma_0 = 116 \pm 4$ and jet opening angle $\theta_j = 12^\circ \pm 2^\circ$.

The empirical function of the mBB can be used to fit the observed data very well. However, the physical meaning of the mBB is still unclear, especially the parameter $q$ of this model, which varies with time. More important observations, or theoretical studies and numerical simulations are expected in the future to explore the physical meaning of the mBB.

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