Detection of Prompt Fast-Variable Thermal Spectral Component in Multi-Pulse Short Gamma-Ray Burst 170206A

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ABSTRACT

We report the detection of strong thermal spectral component in the short Gamma-Ray Burst 170206A with three intensive pulses in its lightcurves, throughout which the fluxes of this thermal component exhibit fast temporal variability same as that of the accompanied non-thermal component. The values of the time-resolved low-energy photon index in the non-thermal component are between about -0.79 and -0.16, most of which are harder than the line-of-death (-2/3) of the synchrotron emission process. In addition, we found the plausible common evolution between the thermal component and the non-thermal component, \( E_{p,\text{CPL}} \propto kT_{BB} \) and \( F_{\text{CPL}} \propto F_{BB}^{2/3} \), where \( E_{p,\text{CPL}} \) and \( F_{\text{CPL}} \) are the peak photon energy and corresponding flux of the non-thermal component, and \( kT_{BB} \) and \( F_{BB} \) are the temperature and corresponding flux of the thermal component, respectively. Finally, we explored the possible physical origins of GRB 170206A, suggesting the photospheric thermal emission and the Comptonization of thermal photons may be responsible for the observational features of GRB 170206A.

Keywords: gamma-ray burst: general methods: data analysis: radiation mechanisms: thermal

1. INTRODUCTION

Gamma-ray bursts (GRBs) are believed to arise from the deaths of massive stars or the coalescence of two compact stellar objects such as neutron stars or black holes, which both have been followed by an expanding fireball with a jet. Many GRBs observed by several missions suggest the prompt gamma-ray emission to be highly non-thermal (Mazets et al. 1981; Fenimore et al. 1982; Matz et al. 1985; Kaneko et al. 2006; Goldstein et al. 2012). Synchrotron emission has been proposed as the most natural radiative process, due to the non-thermal appearance of the observed spectra and to the likely presence of accelerated electrons and intense magnetic fields (Rees & Meszaros 1994; Katz 1994; Tavani 1996; Sari et al. 1996, 1998). Recently, the values of the low-energy photon index (\( \alpha \)) inferred from the observed GRB spectra are in contrast with the predictions from the synchrotron theory, such as \( \alpha \) is harder than -2/3. This low-energy photon index is expected to be -3/2 when the electrons undergo the fast-cooling synchrotron, while to be about -2/3 when the electron spectrum follows in the slow-cooling synchrotron (Sari et al. 1998). A few theoretical models have been proposed to reconcile the observed GRB prompt spectra with the synchrotron process. Some of them invoke effects that produce a hardening of the low-energy spectral index, such as a decaying magnetic field (Pe’er & Zhang 2006; Ulm & Zhang 2014; Zhang 2020; Wang & Dai 2021), inverse Compton scattering in the Klein–Nishina regime or a marginally fast cooling regime (Derishev et al. 2001; Nakar et al. 2009; Wang et al. 2009; Daigne et al. 2011).

Actually, the emission from this fireball is expected to be thermal, which is originated from the non-dissipative photosphere (Goodman 1986; Paczynski 1986; Rees & Meszaros 1994; Ryde 2004; Pe’er 2008; Beloborodov 2010; Pe’er & Ryde 2011; Beloborodov 2011; Ghirlanda et al. 2013; Larsson et al. 2015; Ryde et al. 2017). This pure thermal component fitted by a standard Plank blackbody function is discovered in many Fermi-GBM GRBs, such as GRB 150101B and other GRBs (Burns et al. 2018; Acuner et al. 2019, 2020). Even the \( \alpha \) is accepted in the

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synchrotron theory, the modified thermal processes are proposed to account to the observations, such as the dissipative photosphere (Rees & Mészáros 2005; Veres et al. 2012; Giannios 2012; Lundman et al. 2013, 2014, 2018).

A trend has therefore evolved with the possibility of reconciling synchrotron emission with the α distributions, which consists of fitting a blackbody (non-dissipative photosphere) in combination with the typically fitted non-thermal spectral function to spectra observed by Fermi/GBM (Guiriec et al. 2011; Axelsson et al. 2012; Guiriec et al. 2013; Iyyani et al. 2013; Preece et al. 2014; Burgess et al. 2015; Tang et al. 2021).

Recently, GRB 120323A was the first short GRB (SGRB) with contemporaneous detection of the thermal component and non-thermal component in the prompt phase, with the single-pulse lightcurves and a decaying pattern both in its thermal flux and thermal temperature (Guiriec et al. 2013). Among top ten brightest fluence-selected SGRBs detected by Fermi/GBM as of 2021 December, we have searched for such spectral property, and found that GRB 170206A with a strong thermal-component detection, which however shows very different properties from GRB 120303A, such as the tracking pattern between the thermal component and non-thermal component. In this work, we report the results of this unique SGRB and explore its possible physical origins. The paper is organized as follows. In §2, we present the observations of GRB 170206A. In §3, data analysis of GRB 170206A and the results are presented. In §4, we discuss the origins of these two spectral component. The conclusion and discussion are presented in §5.

2. OBSERVATIONS

GRB 170206A was triggered at 10:51:57.70 UT on 06 February 2017 (T0) by Fermi Gamma-Ray Burst Monitor (GBM) with R.A.\textsubscript{GBM} = 211.80\degree, Decl.\textsubscript{GBM} = 13.06\degree and 1 sigma uncertainty of 1.14 degrees. The GBM lightcurve (LC) shows a short, bright burst with a duration of about 1.2 s in the energy range of 50-300 keV (von Kienlin & Roberts 2017). It was also detected by Fermi Large Area Telescope (LAT) with best location at R.A.\textsubscript{LAT} = 212.79\degree, decl.\textsubscript{LAT} = 14.48\degree and the 90\% containment statistical error radius 0.85 degrees, which is consistent with the GBM position. The angle from the Fermi/LAT boresight at the GBM trigger time (T0) is about 67\degree, the highest-energy photon detected by LAT is about 811 MeV event which is observed 3.17 seconds after the GBM trigger (Dirirsa et al. 2017).

GRB 170206A was detected by Konus-Wind, INTEGRAL/SPI-ACS, and Mars-Odyssey/HEND, with center location of R.A.\textsubscript{IPN} = 212.63\degree and decl.\textsubscript{IPN} = 14.24\degree (Svinkin et al. 2017; Hurley et al. 2017). POLAR on-board the Chinese space laboratory Tiangong-2 detected it in the energy range of about 20-500 keV, which shows that GRB 170206A consists of multiple peaks and with the minimum detectable polarization of about 5.7\% (Wang et al. 2017).

3. DATA ANALYSIS

3.1. Event selections

For the GBM data, three NaI detectors most close to the GRB position (n9, na and nb) and one BGO detector (b1) with the lowest angle of incidence are included. For the time-tagged event (TTE) from these NaI detectors employed in the following sections, we ignore the last two channels and events with photon energy less than 8 keV. For TTE data of the BGO detector, the channels with energy below 200 keV and above 40 MeV are ignored. We choose the time intervals of [-25 s, -10 s] and [15 s, 30 s] away from the GBM trigger time to fit the background. Instrument response files are selected with the \textit{rsp2} files throughout the data analysis.

For the LAT data, the LAT–\textit{Transient020E} events with a zenith angle cut of 100\degree are selected, whose energy are between 100 MeV to 10 GeV. Region of interest (ROI) is chosen within the radius of 12\degree from the Fermi/LAT localization, such as R.A.\textsubscript{LAT} = 212.79\degree, decl.\textsubscript{LAT} = 14.48\degree.

3.2. Temporal analysis

We built the multi-wavelength GBM LCs as well as the LAT LC, which are shown in Figure 1.

For the GBM LCs, we plotted them in three energy bands, such as the low energy band (8-50 keV, hereafter LE band), the energy band employed to estimate the GBM \textit{T}90 (50-300 keV, hereafter \textit{T}90 band), among which 90\% of the burst’s fluence was accumulated, and the main energy range of the BGO detector (300 keV-20 MeV, hereafter BGO band). For those LCs in LE band and \textit{T}90 band, the average count rates of three NaI detectors (n9, na and nb) are calculated. As seen in Figure 1, LCs both in \textit{T}90 band and BGO band show fast-variable property with three intensive pulses, while LC in LE band can be also distinguished by three pulses. In order to performed the time-resolved spectral analysis in the following sections, six epochs are finally derived by rebinning the TTE data of the brightest NaI detector (n9) using the Bayesian Blocks method (BBlocks; Scargle et al. 2013) with a false alarm probability of \textit{p_0} = 0.001.
Table 1. Properties of the high-energy photons detected by Fermi-LAT

| GRB name  | Arrival Time $^a$ | Photon Energy | Probability $^b$ |
|-----------|-------------------|---------------|------------------|
| 170206A   | 0.85 s            | 121.7 MeV     | 36.97%           |
| ...       | 3.17 s            | 810.6 MeV     | 99.99%           |
| ...       | 6.60 s            | 389.0 MeV     | 96.27%           |
| ...       | 61.33 s           | 306.3 MeV     | 65.62%           |
| ...       | 82.51 s           | 105.9 MeV     | 5.55%            |
| ...       | 98.25 s           | 121.5 MeV     | 18.97%           |

$^a$ Arrival time of each high-energy photon after GBM $T_0$

$^b$ Probability of each high-energy photon that associated with GRB 170206A.

which is the chance probability of the correct bin configuration. The derived time-resolved epochs are plotted with the red dashed vertical lines and labeled from epoch a to epoch f, amongst which the epochs b, c and e are dominated by the first pulse (P1), the second pulse (P2) and the third pulse (P3) as seen in Figure 1.

In order to discuss the spectral properties before and after the GBM $T_{90}$ epoch (epochs a+b+c+d+e+f), we perform the same BBlocks analysis as above in the time scales $[-0.500\, \text{s}, 0.208\, \text{s}]$, $[1.376\, \text{s}, 2.000\, \text{s}]$ relative to $T_0$. As a result, we derived two epochs nearest the $T_{90}$, such as Pre-$T_{90}$ epoch of $[T_0-0.133, T_0+0.208]$ and Post-$T_{90}$ epoch of $[T_0+1.376, T_0+1.497]$, which are also employed to perform time-integrated spectral analysis in the following sections.

As for the LAT data, we perform the unbinned likelihood analysis in the time range of 1 seconds before and 100 seconds after the GBM trigger time, and calculate the the probability of each photon that associated with GRB 170206A by the Fermi Science Tools ($gtsrcprob$). As seen in Table 1, there are six high energy photon events detected by Fermi/LAT, however, the only one photon within GBM $T_{90}$ has a probability less than 50%, thus we did not include the LAT data in the following spectral analysis.

3.3. Spectral analysis

3.3.1. General method

Four models are defined to fit the gamma-ray data of GRB 170206A, e.g., the cutoff power-law model (CPL), the Band model (BAND) and two blackbody (BB)-joint models, e.g., the CPL+BB model and the BAND+BB model. For the latter two BB-joint models, the CPL+BB model consists of the CPL component and BB component while the BAND+BB model comprises the BAND component and the BB component. These models are expressed below:

(i) The BAND model, which is written same as that in (Band et al. 1993),

\[
N(E)_{\text{BAND}} = \begin{cases} 
A_{\text{BAND}} (\frac{E}{100\, \text{keV}})^\alpha \exp\left[-\frac{(2+\alpha)}{E_p}\right], & E \leq \frac{\alpha-\beta}{2+\alpha} E_p \\
\left(\frac{(\alpha-\beta)E_p}{(2+\alpha)100\, \text{keV}}\right)\frac{E}{E_p}^{\frac{-\alpha-\beta}{2+\alpha}}(\frac{E}{100\, \text{keV}})^\beta, & E \geq \frac{\alpha-\beta}{2+\alpha} E_p
\end{cases}
\]

where $\alpha$, $\beta$ are the low-energy photon index and the high-energy photon index respectively, and $E_p$ (or $E_{p,\text{BAND}}$) is the peak energy in the $\nu F_\nu$ spectrum.

(ii) The CPL model is written as

\[
N(E)_{\text{CPL}} = A_{\text{CPL}} (\frac{E}{100\, \text{keV}})^\alpha \exp\left[-\frac{E}{E_c}\right],
\]

where $\alpha$ is the photon index and $E_c$ is the cutoff energy. The peak energy of the CPL model ($E_{p,\text{CPL}}$) is calculated by $E_{p,\text{CPL}} = (2 + \alpha) \times E_c$. 

Figure 1. Composite LCs for GRB 170206A. From top to bottom, low energy band lightcurve (8-50 keV, LE band), GBM $T_{90}$ band lightcurve (50-300 keV, $T_{90}$ band), the main BGO energy band lightcurve (BGO band), and the LAT lightcurve (100 MeV–10 GeV, LAT band). The green shadowed region covers the GBM $T_{90}$ epoch, the red shadows before and after which are the Pre-$T_{90}$ epoch, Post-$T_{90}$ epoch respectively, detail please see the text in section 3.2. The red dashed vertical lines divide the GBM $T_{90}$ into six time-resolved epochs, which are labeled from a to f. The empty circle in the bottom panel indicate that the photon event ($>100$ MeV) has a probability <0.9 of being associated with GRB 170206A.

(iii) The BAND+BB model is given by the photon differential flux

$$N(E)_{\text{BAND+BB}} = N(E)_{\text{BAND}} + A_{BB} \frac{E^2}{\exp(E/kT) - 1},$$

where $k$ is the Boltzmann’s constant, and the joint parameter $kT$ as a output parameter in common.

(iv) The CPL+BB model with the photon differential flux

$$N(E)_{\text{CPL+BB}} = N(E)_{\text{CPL}} + A_{BB} \frac{E^2}{\exp(E/kT) - 1}.$$  

Above all, $A$ is the amplitude. The free parameters in a candidate model are constrained in the reasonable ranges, which are presented in Table 2. As seen in Table 2, those free parameters are initialed at the typical spectral parameter values from the Fermi-GBM catalog (von Kienlin et al. 2020) and allowed in the broad ranges.

Other six models are also included to make comparisons, such as the main models (BAND, CPL) with an additional power-law decay model (PL) or the multicolor blackbody (mBB), which are presented in Appendix A. As discussed in Appendix A, the most possible model mBB can not fit the SED well in $T_{90}$ period and three time-resolved spectra, such as epochs b,d and e, thus we did not present it in the following sections.
Table 2. Parameter Setting

| Function | Parameter name | Initial Value | Parameter Range |
|----------|----------------|---------------|-----------------|
| BB       | $A_{BB}, kT_{BB}$ | $10^{-4}, 30$ | $[10^{-3}, 10], [0.1, 3 \times 10^{6}]$ |
| BAND     | $A_{BAND}, \alpha, \beta, E_p$ | $10^{-1}, -1.0, -2.0, 300$ | $[10^{-6}, 10^{4}], [-1.5,5.0], [-1.0, -1.5], [0.1, 3 \times 10^{7}]$ |
| CPL      | $A_{CPL}, \alpha, E_c$ | $10^{-1}, -1.0, 300$ | $[10^{-6}, 10^{4}], [-10.0,10.0], [0.1, 3 \times 10^{7}]$ |

As a common method in the GBM spectral analysis, we employ the maximum likelihood estimate (MLE) method, which is suitable for the Poisson data and the Gaussian background (PGstat; Cash 1979). For each fitting, a likelihood value $L(\vec{\theta})$ as the function of the free parameters $\vec{\theta}$ is derived, then the value of the Akaike Information Criterion (AIC; Akaike 1974), defined as $\text{AIC}=-2\ln L(\vec{\theta})+2k$, and the value of the Bayesian Information Criterion (BIC; Schwarz 1978), defined as $\text{BIC}=-2\ln L(\vec{\theta})+k\ln n$, are calculated, where $k$ is the number of free parameters to be estimated and $n$ is the number of observations (the sum of the selected GBM energy channels). In this work, the Multi-Mission Maximum Likelihood package (3ML; Vianello et al. 2015) are employed to carry out all the spectral analysis and the parameter estimation.

In this paper, given any two estimated models, the preferred model is the one that provides the minimum BIC score, which is often compared as $\Delta\text{BIC}$ scores, that is the difference between the best model and each candidate model. We use $\Delta\text{BIC}$ to describe the evidence against a candidate model as the best model in the spectral analysis of GRB 170206A. With respect to the model with the minimum BIC, if $\Delta\text{BIC}$ is greater than 6, the evidence against the candidate model is strong while $\Delta\text{BIC}$ greater than 10 is very strong (Kass & Raftery 1995). If $\Delta\text{BIC}$ is not larger than 6, the candidate model is the compared model, in which case we prefer to one model with the reasonable parameters. For example, when the high-energy photon index $\beta$ of the BAND model is smaller than -5.0 (unconstrained), then the CPL model is a better model to fit the data than the BAND model, although $\text{BIC}_{\text{BAND}} - \text{BIC}_{\text{CPL}} < 6$.

3.3.2. Time-integrated spectral analysis

We perform the time-integrated spectral analysis of GRB 170206A in three main epochs, that is Pre-$T_{90}$ epoch, $T_{90}$ epoch and Post-$T_{90}$ epoch described in the section 3.2, whose results are presented in Table 3.

For the $T_{90}$ period, the BAND+BB model is not suitable to fit the gamma-ray data with a unconstrained $\beta$, e.g., $\beta < -5.0$. Note that, the BIC value of the CPL+BB model is also 6.1 smaller than that of the BAND+BB model. The CPL+BB model has the minimum BIC value and a $\Delta\text{BIC}$ larger than 6 to other two models, such as 7.5 with respect to the BAND model and 14.4 to the CPL model, thus is considered as the best-fit model. The energy fluxes of the CPL component and the BB component in the CPL+BB model are calculated in the energy range between 8 keV and 40 MeV, such as $F_{\text{CPL}}$, $F_{\text{BB}}$ of $8.7 \pm 1.8 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$, $1.2 \pm 0.5 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ respectively. The BB component takes a temperature of $kT_{\text{BB}} = 43 \pm 4$ keV. The $\nu F_{\nu}$ spectral energy distribution (SED) fitted by the CPL+BB model is plotted at top right of Figure 2.

For the Pre-$T_{90}$ period, one can see that the CPL model is suited for fitting the gamma-ray spectrum with the $\Delta\text{BIC}$ larger than 6 compared to other three models, thus the CPL model is the best-fit model in the Pre-$T_{90}$ epoch, which is plotted at top left of Figure 2.

For the Post-$T_{90}$ period, the parameters could not be constrained well in both BAND and BAND+BB models. The CPL model is the better model to fit the data than the CPL+BB model with $\Delta\text{BIC} = 6.1$. Therefore, the best-fit model for the Post-$T_{90}$ epoch is the CPL model, which is plotted at bottom of Figure 2.

3.3.3. Time-Resolved spectral analysis

Time-resolved spectral analysis of GRB 170206A in six epochs is performed, such as $[T_0+0.208\text{ s}, T_0+0.394\text{ s}]$ for epoch a, $[T_0+0.394\text{ s}, T_0+0.650\text{ s}]$ for epoch b, $[T_0+0.650\text{ s}, T_0+0.782\text{ s}]$ for epoch c, $[T_0+0.782\text{ s}, T_0+1.138\text{ s}]$ for epoch d, $[T_0+1.138\text{ s}, T_0+1.221\text{ s}]$ for epoch e and $[T_0+1.221\text{ s}, T_0+1.376\text{ s}]$ for epoch f. In these spectral fittings, we set the initial spectral parameter values same as the resultant parameter values by spectral analysis in the GBM $T_{90}$ epoch.

Firstly, as seen in Table 3, the time-resolved spectra in all epochs are not well fitted by the BAND+BB model due to the unconstrained high-energy photon index $\beta$ except for epoch d. However in the epoch d, the BIC value derived
by the model of BAND+BB is 9.9 larger than that in the models of CPL, which indicates a worse fit. Therefore, the BAND+BB model is rejected to fit the time-resolved gamma-ray spectra of GRB 170206A.

Secondly, we compare the one-component models, such as the BAND model and CPL model. In the epochs a+c+f, the CPL model is a better model than the BAND model with the ΔBIC is 6.2, 6.1 and 6.0 respectively. For other three epochs (b+c+d), the CPL model in each epoch has a smaller BIC value than that in BAND model, however, the ΔBIC is less than 6, such as 3.7, 3.2 and 4.3 respectively. With less spectral parameters and smaller BIC values, we thus preferred the CPL model for epochs b+c+d. In general, the CPL model is preferred in the one-component model in all time-resolved epochs.

Finally, when comparing the CPL model and the CPL+BB model, the CPL+BB model is a better model than the CPL model in the epoch b with ΔBIC = 11.1. The CPL model is a better model in the epoch a (ΔBIC = 9.6) and epoch f (ΔBIC = 11.2). For epochs c+d, the CPL has a smaller BIC values but with the ΔBIC smaller than 6, such as 5.5, 4.3 respectively, therefore we cannot reject the CPL+BB model in these three epochs. For epoch e, the CPL+BB

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**Table 3. Spectral-fitting results of GRB 170206A**

| Models | Main component | BB component | Stat. & dof |
|--------|---------------|--------------|-------------|
|        | T_start – T_end | α ± β | kT_BB | F_BB | AIC/BIC/-log(likelihood) | dof |
| Time-integrated | | | | | |
| Pre-T₉₀ | 0.133 – 0.208 | | | | |
| BAND | 382 ± 79 | -0.91 ± 0.11 | -5 | 2.0 ± 1.7 | 818.3 / 834.9 / 405.1 | 474 |
| BAND+BB | 10 ± 10 | -0.32 ± 0.21 | -1.66 ± 0.08 | 0.72 ± 0.4 | 836.7 / 861.6 / 412.3 | 472 |
| CPL | 380 ± 116 | -0.91 ± 0.12 | -1.92 ± 1.3 | 9.2 ± 2 | 816.3 / 828.8 / 405.1 | 475 |
| CPL+BB | 328 ± 136 | -0.35 ± 0.46 | -1.60 ± 0.7 | 9.2 ± 2 | 818.6 / 837.6 / 403.4 | 473 |
| Time-resolved | | | | | |
| (a) 0.208 – 0.394 | | | | | |
| BAND | 345 ± 30 | -0.16 ± 0.13 | -5.80 ± 2.74 | 4.7 ± 1.0 | 190.6 / 207.3 / 91.3 | 474 |
| BAND+BB | 359 ± 20 | -0.20 ± 0.15 | 2.95 ± 0.50 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| CPL | 345 ± 53 | -0.16 ± 0.24 | -5.80 ± 2.74 | 4.7 ± 1.0 | 190.6 / 207.3 / 91.3 | 474 |
| CPL+BB | 359 ± 63 | -0.20 ± 0.15 | -5.80 ± 2.74 | 4.7 ± 1.0 | 190.6 / 207.3 / 91.3 | 474 |
| (b) 0.394 – 0.550 | | | | | |
| BAND | 479 ± 39 | -0.22 ± 0.07 | 2.95 ± 0.50 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| BAND+BB | 804 ± 93 | -0.53 ± 0.08 | 2.95 ± 0.50 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| CPL | 529 ± 42 | -0.30 ± 0.05 | 2.95 ± 0.50 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| CPL+BB | 804 ± 136 | -0.53 ± 0.08 | 2.95 ± 0.50 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| (c) 0.550 – 0.782 | | | | | |
| BAND | 331 ± 24 | -0.92 ± 0.10 | -2.96 ± 0.40 | 17.9 ± 3.9 | -23.3 / -23.6 / -15.6 | 474 |
| BAND+BB | 471 ± 11 | -0.33 ± 0.06 | -5.80 ± 2.74 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| CPL | 362 ± 31 | -0.11 ± 0.08 | -5.80 ± 2.74 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| CPL+BB | 470 ± 113 | -0.33 ± 0.17 | 2.95 ± 0.50 | 19.4 ± 3.8 | 937.0 / 953.7 / 464.5 | 474 |
| (d) 0.782 – 1.138 | | | | | |
| BAND | 200 ± 18 | -0.20 ± 0.11 | 3.01 ± 0.61 | 0.6 ± 1.6 | 1163.5 / 1180.1 / 577.7 | 474 |
| BAND+BB | 245 ± 20 | -0.17 ± 0.20 | 4.03 ± 1.31 | 0.4 ± 0.3 | 1160.6 / 1185.6 / 574.3 | 474 |
| CPL | 214 ± 18 | -0.26 ± 0.07 | -5.80 ± 2.74 | 4.7 ± 1.0 | 1163.5 / 1175.8 / 578.6 | 475 |
| CPL+BB | 246 ± 40 | -0.17 ± 0.20 | -5.80 ± 2.74 | 4.7 ± 1.0 | 1163.5 / 1175.8 / 578.6 | 475 |
| (e) 1.138 – 1.221 | | | | | |
| BAND | 541 ± 43 | -0.33 ± 0.08 | -5.41 ± 2.52 | 19.8 ± 3.1 | -503.2 / -576.5 / -300.6 | 474 |
| BAND+BB | 693 ± 86 | -0.21 ± 0.19 | 17.6 ± 2.5 | 35.6 ± 1.7 | -604.2 / -577.4 / -307.2 | 474 |
| CPL | 542 ± 67 | -0.33 ± 0.08 | -5.41 ± 2.52 | 19.8 ± 3.1 | -503.2 / -576.5 / -300.6 | 474 |
| CPL+BB | 693 ± 141 | -0.21 ± 0.19 | 17.6 ± 2.5 | 35.6 ± 1.7 | -604.2 / -577.4 / -307.2 | 474 |
| (f) 1.221 – 1.376 | | | | | |
| BAND | 205 ± 25 | -0.67 ± 0.12 | 3.61 ± 1.58 | 3.4 ± 0.9 | -136.6 / -119.9 / -72.3 | 474 |
| BAND+BB | 253 ± 67 | -0.78 ± 0.23 | -10.0 | 2.9 ± 1.5 | -131.5 / -128.5 / -72.8 | 474 |
| CPL | 210 ± 41 | -0.68 ± 0.12 | 3.61 ± 1.58 | 3.4 ± 0.9 | -136.6 / -119.9 / -72.3 | 474 |
| CPL+BB | 253 ± 112 | -0.79 ± 0.24 | -10.0 | 2.9 ± 1.5 | -131.5 / -128.5 / -72.8 | 474 |
**Figure 2.** Spectral energy distributions and best-fitted model for the time-integrated spectra of GRB 170206A. Top left: Pre-$T_{90}$ epoch between $T_0-0.13$ s and $T_0+0.21$ s. Top right: $T_{90}$ epoch between $T_0+0.21$ s and $T_0+1.38$ s. Bottom: Post-$T_{90}$ epoch between $T_0+1.38$ s and $T_0+1.50$ s. Data points are from the Fermi/GBM. For spectra best-fitted by CPL model, the red solid line represents the resultant CPL model. For spectra best-fitted by the CPL+BB model, the green dotted line represents the CPL component, the red dashed line represent the BB component and the red solid line is the total modeled flux. All red shadow regions are the 95% confidence intervals of the total modeled flux.

model has a smaller BIC than that in the CPL model, i.e., $\Delta$BIC is 1.0, thus the CPL model is a compared model in this epoch.

In totally, the CPL+BB model is the best-fit model in the epoch b, and could be a compared model in the epochs c+d+e. The CPL model is the best-fit model in epochs a+f, and could be a compared model in the epochs c+d+e.

In order to discuss the parameter ans flux variations during the GBM $T_{90}$, we therefore selected the CPL+BB model as the fitting model in the following analysis excepted for epoch a, and all $\nu F_\nu$ SEDs are plotted in Figure 3. Note that, for epoch a, the $\alpha_{CPL}$ in the CPL+BB model is very hard, such as $+2.25(\pm0.72)$, thus finally we prefer the CPL model for epoch a.

In Figure 4, temporal variations of the resultant parameters are plotted as well as the multi-wavelength GBM LCs. In the panel of the CPL index ($\alpha_{CPL}$), the low-energy photon indices of epochs a+b+c+d+e are all out of the synchrotron limit (-2/3), which implies that the CPL component could not be of the standard synchrotron origin. For other epochs, such as Pre-$T_{90}$, f and Post-$T_{90}$, $\alpha_{CPL}$ is also attacking the boundary of the synchrotron limit.

For the peak energy of the CPL component ($E_{p, CPL}$) and the temperature of the BB component ($kT_{BB}$), they track each other well, such as decaying-rising-decaying. The correlation is tested in the time-resolved spectra employing the linear regression method in *Origin* software package, which returns the Pearson correlation coefficient ($R$) and the chance probability of the null hypothesis ($p$). A strong positive correlation can be claimed when $R > 0.8$ while a moderate positive correlation can be claimed when $0.5 < R < 0.8$ (Newton & Rudestam 1999). We find that $kT_{BB}$ is
strong positively correlated with \( E_{p,\text{CPL}} \) with \( R = 0.865 \) and \( p = 0.026 \), such as:
\[
E_{p,\text{CPL}} = 10^{1.20\pm0.42} kT_{\text{BB}}^{0.95\pm0.28},
\]
(5)
as seen in Figure 5, where both \( E_{p,\text{CPL}} \) and \( kT_{\text{BB}} \) are in the unit of keV.

For the energy fluxes in time-resolved epochs derived from the CPL+BB model, the CPL fluxes \( F_{\text{CPL}} \) track the BB fluxes \( F_{\text{BB}} \) well. The correlation analysis between them also favors for a strong positive correlation, such as:
\[
F_{\text{CPL},-6} = 10^{0.88\pm0.08} F_{\text{BB},-6}^{0.67\pm0.18},
\]
(6)
with \( R = 0.884 \) and \( p = 0.019 \), which can be seen in Figure 5. Here, \( F_{-6} = 10^{-6} F \) and both fluxes are in the unit of erg cm\(^{-2}\) s\(^{-1}\).

4. ORIGIN OF THERMAL AND NON-THERMAL COMPONENTS AND ITS IMPLICATIONS

In addition to the four adopted spectral models in Table 3, i.e., BAND, BAND+BB, CPL, and CPL+BB, we have compared other spectral models in Appendix A as well. As we can see, the other models do not present distinct advantages, so next we focus on the four popular spectral models shown in Table 3 to explore the possible physical origins. Table 3 showed the fitting parameters of the spectra for the models of BAND, BAND+BB, CPL and CPL+BB. When the BAND function is involved, either for the single BAND model or the BAND+BB model, usually, a very steep photon index at the higher energy band, namely, a very small \( \beta \), has to be invoked. Such a small value of \( \beta \) makes the BAND function approach the spectral shape of the CPL, implying that the real spectral shape may follow the CPL function rather than the typical BAND function. In addition, for the time-integrated and time-resolved spectra in most cases during the \( T_{90} \) (see Section. 3.3), one can see the CPL+BB model is fitting better comparing with the single CPL model. Although in some cases, a single CPL model is good enough, this may be caused by the different weight of two components (BB and CPL components), inducing one component is overshot by another one. As a result, we take a more complicated observed spectral shape which contains two parts, i.e., a thermal component (the BB component) and a non-thermal component (the CPL component), to study their possible origins.

Besides, from the third and fourth panels of Figure 4, one can see the plausible common evolution between the BB component and the CPL component, indicating a correlation between both components. Figure 5 shows their correlations, i.e., \( E_{p,\text{CPL}} \propto kT_{\text{BB}} \) and \( F_{\text{CPL}} \propto F_{\text{BB}}^{2/3} \). This provides some implications on the origin of the BB component and the non-thermal component as well.

Based on the above analyses, we suggest that the thermal emission and the non-thermal emission could imply two radiation regions (Mészáros et al. 2002). Basically, the thermal emission is a natural prediction from the photosphere of “fireball” model (Mészáros & Rees 2000; Mészáros et al. 2002; Rees & Mészáros 2005). Usually, the photons are coupled with the outflow due to the large optical depth at small radii and the spectrum emerging at the photosphere are shown as the blackbody distribution. Apart from this thermal emission from the photospheric origin, the non-thermal part could originate from the energy dissipation above the photosphere. Thermal photons could serve as seed photons to Compton scattering of energetic electrons above the photosphere and affect the final non-thermal spectrum emitted by these electrons (Pe’er et al. 2005, 2006, 2012; Samuelsson et al. 2021). In other words, the Comptonization of thermal photons shows as an additional non-thermal spectral component to the thermal component. Such a connection between the thermal emission and the non-thermal emission may be responsible for the correlation between the BB component and the CPL component as shown in the third and fourth panels of Figure 4. Moreover, the low-energy spectral index of Comptonized photons, i.e., \( \alpha \), could be harder than the death-line of synchrotron radiation (-2/3), inducing \( \alpha \) ranging from -1.0 to 0.5 in some physical conditions (Deng & Zhang 2014). Such a range of \( \alpha \) value is consistent with the low-energy photon indices listed in Table. 3, especially for those indices which are larger than \(-2/3\) significantly.

Notice that the above suggested physical origin is based on the most preferred spectral functions, i.e., CPL or CPL+BB. The strong correlation between the BB component and the CPL component may be responsible to a single spectral function rather than two spectral functions, such as the mBB function mentioned in Appendix although it has a worse BIC value. In this situation, the above suggested radiation model will be invalid and the actual physical origin could be totally different.

5. CONCLUSION AND DISCUSSION
Figure 3. Same as Figure 2, but for the time-resolved spectra of GRB 170206A during GBM $T_{90}$. 
In this work, we performed the comprehensive analysis of GRB 170206A with the observations by Fermi/GBM and Fermi/LAT in the prompt phase. A fast-variable thermal spectral component is discovered, which has a correlated photon fluxes with the non-thermal component throughout the $T_{90}$. Hard low-energy photon indices ($\alpha$) are found both in the time-integrated spectra and the time-resolved spectra. In the time-resolved spectra, the photon indices ranges from $-0.79$ to $-0.16$, most of which violate the line-of-death (-2/3) of the synchrotron slow-cooling radiation. In addition, we found the plausible common evolution between the thermal component and the non-thermal component, indicating a positive correlation between photon fluxes as well as peak energies of both components. Based on the observational features, we explored the possible radiation models of GRB 170206A.

Assuming the two radiation regions for these two spectral components, the thermal component comes from the photosphere and the non-thermal component is from the Comptonization of thermal component by the energetic electrons above the photosphere. Since thermal photons serve as seed photons to Compton scattering of energetic electrons above the photosphere and thus affect the final non-thermal spectrum emitted by these electrons, the observational hard low-energy photon indices as well as the positive correlation between their photon fluxes can be reproduced.
The thermal component indicates the optical depth of the jet is quite high, which means the mass of the ejected matter is relatively high. Considering the typical short duration and the relatively high peak energy in the spectrum, GRB 170206A should be a typical short GRB, i.e., the progenitor should be either black hole-neutron star merging, or neutron star-neutron star merging. Taking into account the relatively high mass ejection, we may favor the double neutron star origin. Consequently, it is more or less a GRB 170817A like event, and it may also produce a kilonova-like optical emission. With quick optical follow up observation, such as Chinese space station telescope (CSST), one may expect such short GRBs with thermal component can be caught up with the linked kilonova.

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Facilities: Fermi/GBM, Fermi/LAT

Software: 3ML (Vianello et al. 2015)

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## Table A1. ΔBIC between each candidate model and the model with minimum BIC*

| Period | BAND | BAND+BB | BAND+PL | CPL | CPL+BB | CPL+PL | BB | BB+BB | BB+PL | mBB |
|--------|------|---------|---------|-----|--------|--------|----|--------|--------|-----|
| Post-T90 | Unconstrained | Unconstrained | Unconstrained | 0  | 6.1    | Unconstrained | 10.0 | 22.3 | 5.5 | 1.7 |
| Pre-T90 | 6.5 | 33.1 | 34.2 | 0.3 | 9.1 | Unconstrained | 101.5 | 113.8 | 20.8 | 0 |
| T90 | 7.6 | 6.2 | 339.7 | 14.4 | 0 | 26.7 | 1327.3 | 182.7 | 374.5 | 44.8 |
| a | 6.3 | 15.9 | 39.6 | 0.1 | 9.7 | Unconstrained | 51.2 | 3.6 | 23.0 | 0 |
| b | 14.8 | 6.2 | 143.0 | 11.1 | 0 | 23.5 | 385.5 | 63.6 | 138.5 | 22.0 |
| c | 3.2 | 12.1 | 108.7 | 0 | 5.5 | 11.6 | 178.1 | 26.4 | 52.2 | 3.9 |
| d | 4.4 | 9.9 | Unconstrained | 0 | 4.4 | 11.4 | 285.0 | 9.1 | 76.0 | 6.5 |
| e | 7.1 | 6.2 | 68.9 | 0.9 | 0 | 13.3 | 183.6 | 1.1 | 101.2 | 6.8 |
| f | 6.0 | 17.4 | Unconstrained | 0 | 11.2 | 8.1 | 112.6 | 14.1 | 20.7 | 2.2 |

*ΔBIC of the model with minimum BIC is presented as 0.

## APPENDIX

### A. COMPARISONS ON TEN SPECTRAL MODELS IN GRB 170206A

By including six more spectral models, there are ten spectral models are employed to fit the time-integrated and time-resolved SEDs of GRB 170206A and are selected to make comparisons. For example, the multicolor blackbody model (mBB), a single standard blackbody model (BB), double BB model (BB+BB), BB plus an additional powerlaw decay model (BB+PL), BAND with an additional PL model (BAND+PL) and CPL with an additional PL model (CPL+PL). For the mBB model, the same photon spectral function is employed as that in Iyyani & Sharma (2021), that is the model named diskpbb in Xspec, which can be written as,

\[
N(E) = \frac{4\pi E^2}{h^2 c^2} \left( \frac{A_{mBB}}{\zeta} \right) T_p^{(2/\zeta)} \int_{T_{min}}^{T_p} \frac{T^{-2+\zeta}}{e^{E/T} - 1} dT
\]

where \( A_{mBB} \) is the amplitude, \( \zeta \) is power law index of the radial dependence of temperature (\( T(r) \propto r^{-\zeta} \)), \( T_p \) is the peak temperature in keV and \( T_{min} \) is the minimum temperature of the underlying blackbodies and is considered to be well below the energy range of the observed data, i.e., 8 keV in this work. For the PL function above, its photon model is presented as,

\[
N(E) = A_{PL} \left( \frac{E}{100 \text{ keV}} \right)^\Gamma
\]

where \( A_{PL} \) is the amplitude, \( \Gamma \) is the power law spectral index.

As seen in Table A1, there are three candidate models with ΔBIC close to 0, that is mBB, CPL and CPL+BB. For the Pre-T90 and Post-T90 phase, the CPL and the mBB models are the compared models. However, in the T90 phase, the CPL+BB model is the unique best model to fit its SED, which has none compared models. In the time-resolved spectra, the CPL model is the compared/best model in epochs a+c+d+e+f, the mBB model is the compared/best model in epochs a+c+f and the CPL+BB model is the compared/best model in epochs b+c+d+e.

We did not present the result of the mBB model in the main text for two reasons. On the one hand, the mBB model is ruled out in T90 period and three epochs (b+d+e), which includes two intensive main pulses, such as P1 and P3. On the other hand, the CPL model usually has a smaller BIC than that in the mBB model, such as in epochs c+f, even in epoch a, the mBB model has a BIC only 0.1 smaller than that in the CPL model. Therefore, we did not present the details of the mBB model in the main text. Although the BAND or BAND+BB model with ΔBIC mostly larger than 6 as seen in Figure A1, we include them in the main text since they are the popular models being considered in many published papers.
Figure A1. $\Delta$BIC between each candidate model and the model with minimum BIC. Post, Pre and T90 represent the time-integrated spectra in Post-$T_{90}$, Pre-$T_{90}$ and $T_{90}$ phase. The label a to e are the time-resolved spectra in six epochs between $T_{90}$ duration. For three shadow regions, models in the dark red region (Top) with $\Delta$BIC larger than 10, thus all candidate models are rejected with a very strong evidence; models in the dark grey region (Middle, $6 < \Delta$BIC $< 10$), the candidate models are not recommended with a strong evidence; models in the dark green region (Bottom, $\Delta$BIC $< 6$) are the compared models with respect to the model with the minimum BIC.