



Prevalence of Extra Power-Law Spectral Components in Short Gamma-Ray Bursts

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Abstract

A prompt extra power-law (PL) spectral component that usually dominates the spectral energy distribution below tens of keV or above ~ 10 MeV has been discovered in some bright gamma-ray bursts (GRBs), however, its origin is still unclear. In this paper, we present a systematic analysis of 13 Fermi short GRBs, as of 2020 August, with contemporaneous keV–MeV and GeV detections during the prompt emission phase. We find that the extra PL component is a ubiquitous spectral feature for short GRBs, showing up in all 13 analyzed GRBs. The PL indices are mostly harder than -2.0 , which may be well reproduced by considering the electromagnetic cascade induced by ultrarelativistic protons or electrons accelerated in the prompt emission phase. The average flux of these extra PL components positively correlates with that of the main spectral components, which implies they may share the same physical origin.

Unified Astronomy Thesaurus concepts: [Gamma-ray bursts \(629\)](#); [High energy astrophysics \(739\)](#); [Astronomy data analysis \(1858\)](#)

1. Introduction

Gamma-ray bursts (GRBs) are the most energetic explosions in the universe. They can be divided into two phenomenological categories based on their duration in the prompt phase, namely, long GRBs (LGRBs) and short GRBs (SGRBs), separated at about 2 s. Various physical models have been proposed to explain the prompt emission, such as the photospheric model (Rees & Mészáros 2005; Giannios & Spruit 2007; Pe'er 2008; Beloborodov 2011), the internal shock model (Rees & Mészáros 1994; Kobayashi et al. 1997; Daigne & Mochkovitch 1998) and the magnetic reconnection model (Spruit et al. 2001; Zhang & Yan 2011). Spectral analysis is thus the key to investigate the GRB radiation mechanism and can help us to understand their underlying physical processes. Observationally, GRB prompt emission exhibits diverse spectral properties. Those spectra in the keV–MeV energy range can generally be fitted by some empirical functions, such as the Band function (BAND component) (Band et al. 1993), a simple power-law function (PL component) with a high-energy exponential cutoff function (CPL component) and a smoothly broken PL function (SBPL component), based on 10 yr of observations by the Gamma-ray Burst Monitor (GBM) on board Fermi (Poolakkil et al. 2021), hereafter the GBM catalog.

Combining these the observations of the Large Area Telescope (LAT) on board Fermi, it is interesting to note that the keV–GeV spectra of some GRBs consist of more than one component, for example, a BAND component with a PL component for GRB 080916C, GRB 090510, GRB 0909026A, and GRB 110731A (Ryde et al. 2010; Ackermann et al. 2010, 2013); a CPL component with a PL component for GRB 090902B (time-integrated), GRB 100414A, and GRB 160709A (Ackermann et al. 2013; Tak et al. 2019); and a blackbody component (BB or multi-BB) with a PL component for GRB 081221, GRB 090902B (time-

resolved) 110920A, GRB 160107A, and GRB 160709A (Basak & Rao 2013; Ryde et al. 2010; Iyyani et al. 2015; Kawakubo et al. 2018; Tak et al. 2019).

There are 186 GRBs reported in the 10 yr catalog (hereafter LAT catalog) of Fermi–LAT (Ajello et al. 2019), from 2008 August to 2018 August, among which 169 are LGRBs and 17 are SGRBs. In previous studies, only two SGRBs, namely, GRB 090510 and GRB 160709A, were discovered to show the extra PL component in the spectrum (Ackermann et al. 2010; Tak et al. 2019). In order to further search for and explore the properties of the extra PL component, here we perform a comprehensive joint spectral analysis of Fermi–GBM and Fermi–LAT data of selected SGRBs in the 8 keV–10 GeV energy range detected between 2008 August and 2020 August. The same analysis for LGRBs will be performed and reported elsewhere.

The physical origin of the extra PL spectral components has been extensively explored in the framework of both internal dissipation models (Asano et al. 2009; Bošnjak et al. 2009; Corsi et al. 2010a; Asano & Mészáros 2011; Arimoto et al. 2020) and external dissipation models (Mészáros & Rees 1998; Kumar & Barniol Duran 2009; Beloborodov et al. 2014; Fraija et al. 2017), although the latter may have difficulty in explaining the correlated temporal behavior of the GeV emission and keV–MeV emission in some GRBs (Tang et al. 2017). Even in the internal dissipation models, it is not clear yet from which mechanism the extra PL component arises. As shown in previous literature, either the photopion production or the Bethe–Heitler pair production of relativistic protons can reproduce the additional spectrum component at GeV band. Aside from the hadronic origin model, the inverse Compton (IC) scattering of high-energy electrons can also reproduce such a spectral feature (Wang et al. 2018). Therefore, it may be difficult to reveal the origin of the extra component solely from GeV observations. As will also be discussed in this study, observations at lower energies may provide a clue to differentiate these models.

The rest of the paper is organized as follows. In Section 2, we perform the spectral analysis of selected GRBs. In Section 3, the



Table 1
Durations and Positions of 13 GRBs in Our Sample

GRB	GBM T_0^a (s)	GBM T_{90} (s)	GBM T_{05} (s)	GBM T_{95}	LLE Detection ^b	LAT R.A. ^c	LAT Decl. ^c	LAT Ref. ^d
081024B	246576161.864	0.640	-0.064	0.576	Yes	323.01	20.84	(1)
081102B	247308301.506	1.728	-0.064	1.664	L	212.95	30.33	L
090227B	257452263.407	0.304	-0.016	0.288	Yes	11.80	32.20	L
090228A	257489602.911	0.448	0	0.448	L	98.60	-28.79	L
090510	263607781.971	0.960	-0.048	0.912	Yes	333.57	-26.62	L
110728A	333508824.816	0.704	-0.128	0.576	L	173.57	4.34	L
120830A	368003226.533	0.896	0	0.896	L	88.59	-28.79	L
120915A	369360044.638	0.576	-0.320	0.256	L	240.95	57.04	L
140402A	418090209.998	0.320	-0.128	0.192	L	207.66	5.97	L
141113A	437559466.503	0.448	-0.064	0.384	L	182.32	77.38	L
171011C	529442792.946	0.480	-0.448	0.032	L	168.48	10.03	L
160709A	489786547.512	0.448	0.320	0.768	Yes	236.11	-28.51	(2)
190515A	579587588.135	1.264	-0.112	1.152	L	137.69	29.28	(3)

Notes.

^a GBM burst trigger time in the format of the Fermi Mission Elapsed Time.

^b "Yes" indicates that Fermi-LAT Low-Energy (LLE) data are available.

^c Central position employed for the Fermi-LAT detection.

^d (1) Ajello et al. (2019); (2) Tak et al. (2019); (3) Kocevski et al. (2019).

^e For GRB 160709A, the selected time range is the main prompt GRB emission phase reported in Tak et al. (2019).

spectral fitting results are presented and discussed. In Section 4, we discuss the possible origin of the PL spectral component. The conclusions are presented in Section 5.

2. Methodology

2.1. Sample Selection

The main criterion employed to select our sample is that high-energy photons need to be detected by the Fermi-LAT instrument during the GBM T_{90} interval, during which 90% of the burst fluence (50–300 keV) is accumulated. With a contemporaneous detection by the LAT and the GBM, we thus can perform a broadband spectral analysis between GBM T_0 and GBM T_{95} , which are the start and end of GBM T .

Among the 17 short bursts presented in the LAT catalog, we exclude 5 GRBs with no high-energy photons detected above 100 MeV during the GBM T intervals, i.e., GRB 090531B, GRB 110529A, GRB 160829A, GRB 170127C, and GRB 180703B. Moreover, we also exclude GRB 160702A as its GBM data are not archived in the GBM catalog. Furthermore, we include in our sample a short burst GRB 190515A (Kocevski et al. 2019), that satisfies our selection criterion and was detected after LAT catalog time period, namely between 2018 August and 2020 August. Finally, we also include the long GRB 160709A, although both catalogs classify it as a long burst. Indeed, Tak et al. (2019) classify it as a short hard GRB. In the spectral analysis, we only consider the main bursting phase of GRB 160709A, ranging from 0.32 to ~0.77 s post-trigger time, as discussed in Tak et al. (2019).

Our sample includes 13 SGRBs from 2008 August to 2020 August, which are listed in Table 1, where the GBM trigger time (T_0 in Mission Elapsed Time, MET), T_{90} , T_{05} , and T_{95} are reported. Positions reported by the LAT catalog are employed for the LAT data reduction as shown in Table 1.

2.2. Event Selection and Background Estimation

Fermi-GBM and Fermi-LAT data are used in our spectral analysis. For four GRBs shown in Table 1, Fermi-LAT Low-Energy (LLE) data are also combined in the spectral fitting. All

data are available in the High Energy Astrophysics Science Archive Research Center.⁶

GBM data. For each GRB, we select the three NaI detectors closest to the GRB position and one BGO detector with the lowest angle of incidence, which are presented in Table 2. We analyze NaI time-tagged event (TTE) data with energy between 8 and 900 keV as well as BGO TTE data with energy between 250 keV and 40 MeV, excluding the overflow channels. The GBM backgrounds are usually estimated by fitting the observed TTE data tens of seconds before and after the source emission intervals. Because of the short durations (<2 s) in our sample, we found that two time intervals are reasonable to derive a good count-rate background for the selected GRB detectors through autodetermined polynomial order fitting, such as [-25, -10] and [15, 30] away from the GBM trigger time. Instrument response files are selected with the rsp2 files; however, if no rsp2 files are included in the archived GBM data for some GRBs, such as GRB 120830A, GRB 120915A, GRB 140402A, and GRB 141113A, the rsp files are selected because our spectral analysis is performed for the GRBs with relatively short durations (von Kienlin et al. 2014; Narayana Bhat et al. 2016).

LLE data. There are four GRBs in our sample with LLE detection as shown in Table 1, such as GRB 081024B, GRB 090227B, GRB 090510, and GRB 160709A. Events with energy between 20 and 100 MeV are selected in our spectral analysis. The reduction of the LLE data is the same as that of the GBM data when estimating the background.

LAT data. LAT-Transient020E events with a zenith angle cut of 100° are selected for each burst, whose energy are between 100 MeV and 10 GeV. For GRB 090510, the highest photon energy is about 80 GeV; thus the maximum energy is 100 GeV. Region of interest (ROI) is chosen within the radius of 12° from the localization report in Table 1.

After the event selection, the count-rate light curve is built for each GRB. For example, the composite light curve for GRB 081024B is shown in Figure 1.

⁶ <https://fermi.gsfc.nasa.gov/ssc/data/access/>

Table 2
Information for the Selected GBM Detectors

GRB name	First Na	D ^a (degree)	Second Na	D ^a (degree)	Third Na	D ^a (degree)	BGO	D ^a (degree)
081024B	n0	30.98	n6	23.56	n9	27.67	b1	73.66
081102B	n0	30.66	n1	18.99	n5	44.20	b0	45.46
090227B	n1	27.27	n2	19.31	n5	51.05	b0	54.22
090228A	n0	10.35	n1	24.73	n3	40.40	b0	67.17
090510	n0	34.17	n6	7.07	n7	32.68	b1	81.59
110728A	n0	31.01	n1	33.34	n9	28.14	b1	87.21
120830A	n0	22.98	n1	21.41	n3	39.17	b0	53.13
120915A	n0	17.40	n3	36.17	n6	28.08	b0	79.00
140402A	n0	28.28	n3	32.60	n6	20.26	b0	84.18
141113A	n3	33.64	n6	38.46	n7	33.70	b1	89.78
160709A	n3	13.06	n4	42.93	n6	44.79	b0	70.29
171011C	n0	25.21	n1	23.77	n3	37.08	b0	51.29
190515A	n0	38.36	n1	43.30	n9	18.98	b1	77.38

Note.

^a Angular separation between the pointing of the GBM detector and the GRB position in a unit of degree

2.3. Fitting Models

In order to test the existence of the additional PL spectral component, six typical empirical functions are employed as the fitting models to fit the broadband gamma-ray data of each GRB, which are described below:

(i) The blackbody (BB) function which is usually modified by the Planck spectrum and given by the photon flux

$$\frac{dN}{dE} = A_{BB} \frac{E^2}{\exp[E/kT] - 1}, \quad (1)$$

where k is the Boltzmann's constant, and the joint parameter kT is an output parameter in common. It is found the peak energy in the $E^2 dN/dE$ spectrum of the BB is about 3.92 times the value of kT , that is, $E_{p,BB} \approx 3.92kT$. In all the functions here and below, A is the normalization constant.

(ii) The Band function (BAND), which is written in the same way as in Band et al. (1993),

$$\frac{dN}{dE} = A_{BAND} \left\{ \left(\frac{E}{100 \text{ keV}} \right)^{\alpha} e^{-(2+\alpha)E/E_p}, \quad E \leq \frac{a-b}{2+a} E_p \right. \\ \left. \left\{ \left(\frac{(a-b)E_p}{(2+a)100 \text{ keV}} \right)^{(a-b)} e^{(b-a)E/E_p} \left(\frac{E}{100 \text{ keV}} \right)^{\beta}, \quad E \geq \frac{a-b}{2+a} E_p \right\} \right. \quad (2)$$

where α and β are the low-energy photon index and high-energy photon index respectively, and E_p is the peak energy in the $E^2 dN/dE$ spectrum, which is reported in Section 4. Results as

$E_{p,BAND}$

(iii) The cutoff power-law model (CPL) written as

$$\frac{dN}{dE} = A_{CPL} \left(\frac{E}{100 \text{ keV}} \right)^{\alpha} e^{-E/E_c}, \quad (3)$$

where α is the photon index and E_c is the cutoff energy, the peak energy in the $E^2 dN/dE$ spectrum for the CPL ($E_{p,CPL}$) equals $(2+\alpha)E_c$, say, $E_{p,CPL} = (2+\alpha)E_c$.

(iv) The composite function of the BB and a simple power-law function (BB+PL), that is,

$$\frac{dN}{dE} = \left(\frac{dN}{dE} \right)_{BB} + A_{PL} \left(\frac{E}{100 \text{ keV}} \right)^{\Gamma_{PL}}, \quad (4)$$

where $\left(\frac{dN}{dE} \right)_{BB}$ is the same as Equation (1) and Γ_{PL} is the photon index of the PL function.

(v) The composite function of the BAND and a simple power-law function (BAND+PL), that is,

$$\frac{dN}{dE} = \left(\frac{dN}{dE} \right)_{BAND} + A_{PL} \left(\frac{E}{100 \text{ keV}} \right)^{\Gamma_{PL}}, \quad (5)$$

where $\left(\frac{dN}{dE} \right)_{BAND}$ is the same as Equation (2) and Γ_{PL} is the photon index of the PL function.

(vi) The composite function of the CPL and a simple power-law function (CPL+PL), that is

$$\frac{dN}{dE} = \left(\frac{dN}{dE} \right)_{CPL} + A_{PL} \left(\frac{E}{100 \text{ keV}} \right)^{\Gamma_{PL}}, \quad (6)$$

where $\left(\frac{dN}{dE} \right)_{CPL}$ is the same as Equation (3) and Γ_{PL} is the photon index of the PL function.

2.4. Spectral Fitting and the Best-fitting Model Selection

In this work, we use the Markov Chain Monte Carlo (MCMC) fitting technique based on the Bayesian statistic by using the Multi-Mission Maximum Likelihood package (3ML; Vianello et al. 2015) to carry out all spectral analyses and parameter estimation which requires the corresponding informative priors and the posterior sampling of the parameter space in each fitting model.

2.4.1. Informative Priors Selection

The informative priors are adopted by using the typical spectral parameters from the Fermi-GBM catalog (Poolakkil et al. 2021), hereafter we call it typical priors (TP). For all parameters in the TP scenario, we set the initial parameter values and the parameter range to be the same as the default value in the 3ML package except for the normalization (A), whose lower bound and upper bound are calculated as 10^{-1} and 10^6 times its initial value, respectively. The distribution of the normalization (A) is the logarithm uniform distribution (LogU), the photon indices (α , β , and Γ) have a Gaussian distribution (G), and parameters in units of keV, E_c , and kT are distributed in a logarithm normal distribution (LogN). For

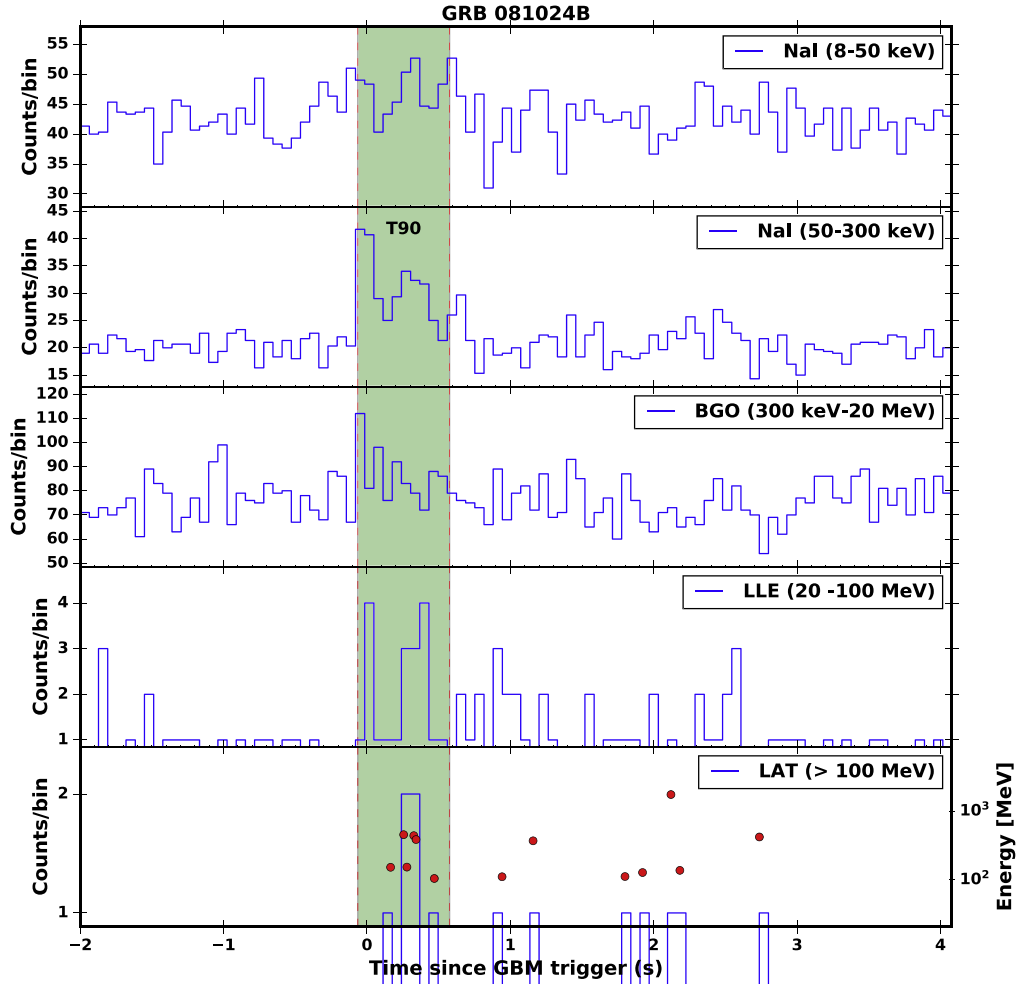


Figure 1. Composite light curve for GRB 081024B. The average count rate of three Nal detectors (the first two panels), BGO (the third panel), LLE (the fourth panel) and LAT transient-class events above 100 MeV within a 12° ROI (bottom panel). The shadowed region is the selected time interval to be analyzed. The filled circle are events that have a probability >0.9 of being associated with the GRB.

Table 3
Prior Setting

Function	Parameter	Initial Value	Parameter Range	TP Scenario ^a
PL	A, Γ	10^{-4} , -2.0	$[10^{-9}, 10]$, $[-10.0, 10.0]$	logU, G
BB	A, kT	10^{-4} , 30	$[10^{-9}, 10]$, $[0, 10^7]$	logU, LogN
BAND	A, α , β , E_p	10^{-4} , -1.0, -2.0, 500	$[10^{-9}, 10]$, $[-1.5, 3.0]$, $[-5.0, -1.6]$, $[0, 10^7]$	logU, G, G, LogN
CPL	A, α , E_c	10^{-4} , -2.0, 30	$[10^{-9}, 10]$, $[-10.0, 10.0]$, $[0, 10^7]$	logU, G, LogN

Note.

^a For the typical priors (TP), LogU represents the logarithm uniform distribution, G represents the Gaussian distribution, and LogN is the logarithm normal distribution.

all Gaussian distributions (G), the central value (μ) equals the initial parameter value and the one standard deviation (σ) is fixed at 0.5. For all logarithm normal distributions (logN), both μ and σ are at the initial parameter values. The TP scenario has been used in several publications for the spectral analysis of the Fermi-GBM GRBs (Li 2019; Yu et al. 2019; Li et al. 2021). The details of these priors are presented in Table 3. For the composite models (BB+PL, BAND+PL, and CPL+PL), we use the joint informative priors above. We also test the uniform priors (UP) for all spectral parameters, whose initial values and parameter ranges are the same as those in the TP scenario but uses multiple walkers to explore the parameter space of the posterior. For each sampling, we set the number of chains (walkers) to 20; the number of learning samples to 3000, which

conclusion that the resultant parameters in both scenarios are consistent with each other; therefore, the results in the TP scenario are presented in the following sections.

2.4.2. Posterior Sampling and the Best-fitting Model Selection

We employ emcee, a sampling method included in the 3ML package to sample the posterior, which is an extensive pure-Python implementation of Goodman & Weare's Affine Invariant MCMC Ensemble sampler (Goodman & Weare 2010). emcee uses multiple walkers to explore the parameter space of the posterior. For each sampling, we set the number of chains (walkers) to 20; the number of learning samples to 3000, which

Table 4
 ΔBIC and the Best-fitting Models

GRB	BB	BAND	CPL	BB+PL	BAND+PL	CPL+PL	Best Model ^a
081024B	>10 ^b	>10	>10	0	>10	>10	BB+PL
081102B	>10	>10	>10	0	>10	>10	BB+PL
090227B	>10	>10	>10	>10	>10	0	CPL+PL
090228A	>10	>10	>10	>10	3	0	CPL+PL
090510	>10	>10	>10	>10	0	>10	BAND+PL
110728A	>10	>10	>10	0	>10	>10	BB+PL
120830A	>10	>10	>10	>10	>10	0	CPL+PL
120915A	>10	>10	>10	0	>10	>10	BB+PL
140402A	>10	>10	>10	0	>10	>10	BB+PL
141113A	>10	>10	>10	0	>10	>10	BB+PL
160709A	>10	>10	>10	>10	3	0	CPL+PL
171011C	>10	>10	>10	0	>10	>10	BB+PL
190515A	>10	>10	>10	0	>10	>10	BB+PL

Notes.

^a Best-fitting model with $\Delta\text{BIC} = 0$.

^b >10 represents the best model against this candidate model.

we do not include in the final results; and the number of global samples to 15,000. MCMC fittings are performed twice, one with the initial parameter values, and the other one with the resultant median parameter values.

In order to know which of a suite of models best represents the data, two information criteria are usually presented to choose the best-fitting model for our sampling SGRBs, such as the Akaike Information Criterion (AIC; Akaike 1974) and the Bayesian Information Criterion (BIC; Schwarz 1978). Here we prefer the BIC for selecting a best-fitting model due to the large sampling in our MCMC fittings. Given any two estimated models, the preferred model is the one that provides the smaller BIC value. Here we use the difference in BIC value ($\Delta\text{BIC} = \text{BIC}_{\text{model B}} - \text{BIC}_{\text{model A}}$) to describe the evidence against a candidate model (model B) to the best model (model A) in the model comparisons. If ΔBIC is larger than 10, the evidence against the candidate model is very strong (Kass & Raftery 1995).

3. Results

3.1. Best-fitting Models

Comparison results of different models of 13 SGRBs are presented in Table 4. We identify three subclasses according to the best-fit models: eight GRBs are best fitted by the BB+PL model (Class A), four GRBs by the CPL+PL model (Class B), and GRB 090510 by the BAND+PL model (Class C). The spectral energy distributions (SEDs) for 3 GRBs from each subclass, namely GRB 081024B, GRB 090227B, and GRB 090510, are plotted together with the marginal posterior distributions in Figure 2, while the SEDs for the other 10 GRBs are shown in Appendix Figures B2 and B3. In all SEDs, we calculated the residual values $(f_{\text{obs}} - f_{\text{m}})^2 / s_{f_{\text{obs}}}^2$, where f_{obs} , $s_{f_{\text{obs}}}$ are the binned observational data and the corresponding 1σ errors, and f_{m} are the fluxes calculated by the best-fitting models. All residuals in 13 GRBs are between 0 and 3.0, which imply good spectral fittings for all GRBs. All resultant parameters of the best-fitting models are presented in Table 5.

Hereafter, we categorize the BB, BAND, and CPL functions as the main component and the PL function as the extra PL component. The extra PL component is present in all 13 analyzed SGRBs, which might imply the common existence of an extra energy dissipation process in SGRBs.

3.2. Parameter Distributions

For the main components, we calculate the peak energy (E_p) in the $E dN/dE$ spectrum. For the standard BB component, the peak energy is found to be about 3.92 times kT_{BB} in our sample, that is, $E_{p,\text{BB}} \approx 3.92 kT_{\text{BB}}$, which is also employed in Zhang et al. (2020) and Tak et al. (2019). For the CPL component, the peak energy is calculated as $E_p = (2 + \alpha)E_c$. The values of the peak energy ($E_{p,\text{BB}}$, $E_{p,\text{CPL}}$ and $E_{p,\text{BAND}}$) are reported in Table 5. As shown in Figure 3, E_p ranges from ~ 200 keV to ~ 3 MeV. We found that the peak energies of the main components of GRBs that are best-fitted with CPL or BAND are larger than those best-fitted with BB.

For the extra component, the observed spectra are generally hard, with the spectral index α ranging from ~ -2.1 to ~ -1.5 , e.g., 10 out of 13 GRBs in our sample with central values of α larger than -2.0 . Note that it does not necessarily mean the absence of a softer PL component in reality, because GRBs with softer PL components may not be detectable to Fermi-LAT.

3.3. Correlation between F_{main} and F_{PL}

Spectral fluxes between 8 keV and E_{max} (the maximum photon energy detected by Fermi-LAT) are calculated by integrating the $E dN/dE$ spectrum, denoted by F_{main} for the main component and F_{PL} for the extra PL component. Then, we test the correlation between them by a linear fit in logarithm space, such as

$$\log F_{\text{PL}} = m + n \log F_{\text{main}}, \quad (7)$$

where m and n are the free parameters. This fitting is performed by the basic linear regression analysis in the popular Origin scientific package, which can give the coefficient of determination (R^2 , $0 < R^2 < 1$). For the linear fit, two variables, such as F_{main} and F_{PL} in our work, are positively correlated if the Pearson correlation coefficient ($R_1 < R < 1$) is close to 1.

We found a moderate correlation between F_{main} and F_{PL} for all GRBs in our sample, with $R = 0.62$, $m = -2.17 \pm 1.67$, and $n = 0.80 \pm 0.31$. The best fit for the correlation is written as

$$\log F_{\text{PL}} = 10^{-2.17 \pm 1.67} + (0.80 \pm 0.31) \log F_{\text{main}}, \quad (8)$$

where both F_{PL} and F_{main} are in units of $\text{erg cm}^{-2} \text{s}^{-1}$. This correlation is plotted in the left panel of Figure 4, in which two

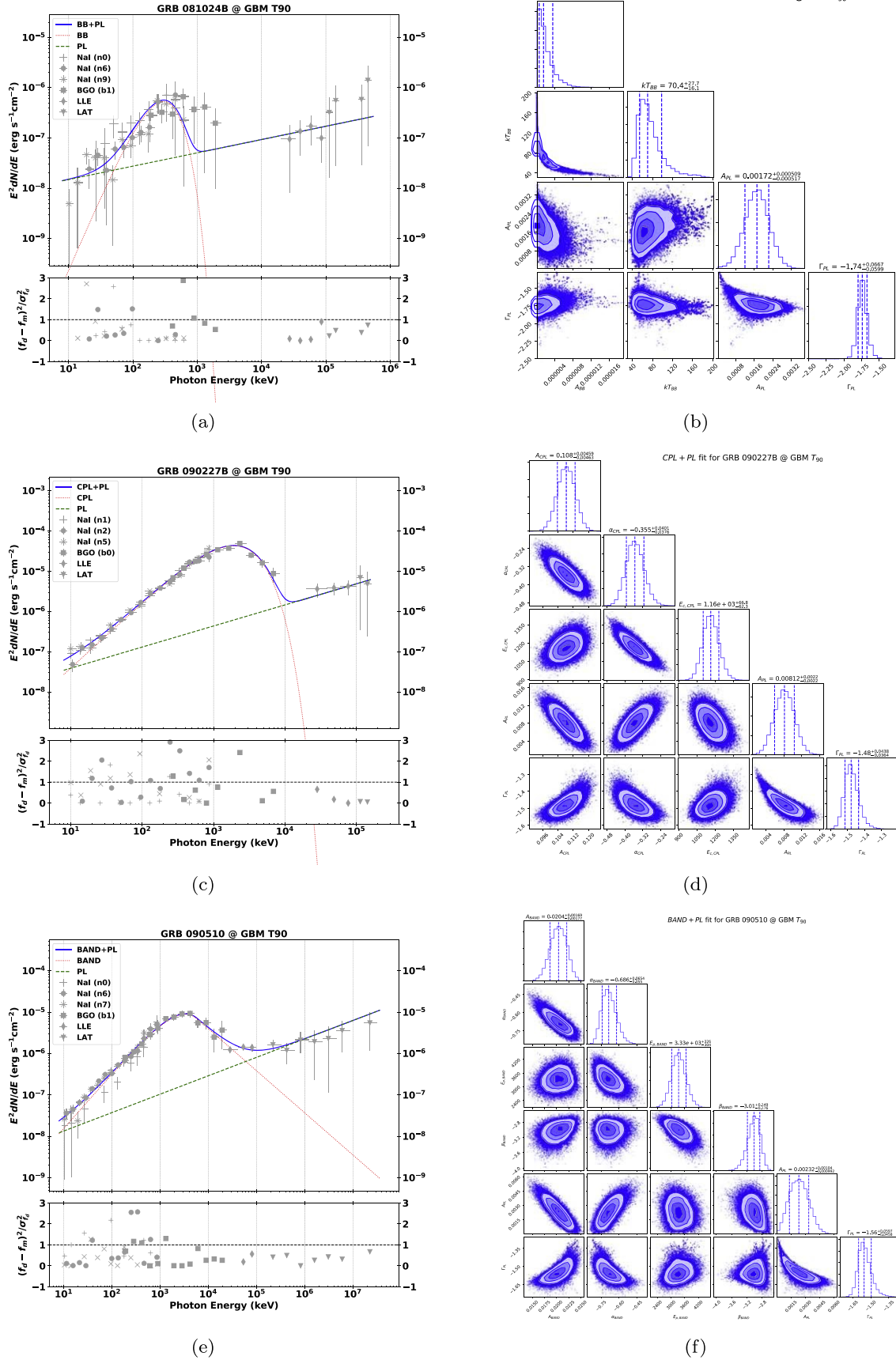


Figure 2. Best-fitting spectral energy distributions (SEDs) and the marginal posterior distributions for SGRBs in our sample. In each SED (a, c, e), gray points are the binned observational data by Fermi, the red dotted line is the modeled main component, the green dashed line is the modeled extra PL component, and the blue solid line represents the sum of both components.

Table 5
Derived Parameters of the Best-fitting Model in the TP Scenario

Class	Main Component		Extra PL Component				
	A_{BB}^a		$E_{\text{p, BB}}^b$	F_{BB}^c	A_{PL}^d	Γ_{PL}	F_{PL}^e
BB+PL							
081024B	19.9 ± 15.0		301 ± 86	7.2 ± 5.4	171.0 ± 51.3	-1.74 ± 0.06	9.1 ± 2.7
081102B	13.1 ± 4.5		297 ± 32	4.4 ± 1.5	161.0 ± 41.8	-1.85 ± 0.12	5.4 ± 1.4
110728A	23.6 ± 11.5		244 ± 40	3.7 ± 1.8	17.9 ± 17.7	-1.93 ± 0.42	0.4 ± 0.4
120915A	12.5 ± 4.5		347 ± 42	8.0 ± 2.9	9.9 ± 9.6	-1.89 ± 0.42	0.2 ± 0.2
140402A	3.8 ± 1.4		588 ± 79	20.0 ± 7.5	19.8 ± 18.7	-2.13 ± 0.52	0.3 ± 0.2
141113A	3.0 ± 1.6		539 ± 111	11.3 ± 5.9	58.7 ± 53.7	-1.87 ± 0.35	1.7 ± 1.6
171011C	23.8 ± 3.5		209 ± 46	69.7 ± 1.5	17.2 ± 14.8	-1.90 ± 0.46	0.4 ± 0.4
190515A	2.4 ± 0.6		679 ± 114	22.2 ± 5.9	49.8 ± 40.3	-1.83 ± 0.25	1.7 ± 1.4
CPL+PL	A_{CPL}^a	α_{CPL}	$E_{\text{p, CPL}}^b$	F_{CPL}^c	A_{PL}^d	Γ_{PL}	F_{PL}^e
090227B	10.8 ± 0.5	-0.35 ± 0.04	1915 ± 106	886.0 ± 37.7	813.0 ± 220.0	-1.48 ± 0.04	106.0 ± 28.7
090228A	10.0 ± 0.4	-0.27 ± 0.09	767 ± 85	192.0 ± 8.7	438.0 ± 238.0	-2.06 ± 0.22	6.0 ± 3.3
120830A	2.0 ± 0.1	-0.16 ± 0.11	1005 ± 159	67.2 ± 4.1	23.8 ± 23.5	-2.02 ± 0.43	0.4 ± 0.4
160709A	2.6 ± 0.2	-0.13 ± 0.08	1784 ± 180	269.0 ± 23.1	380.0 ± 100.0	-1.66 ± 0.05	24.7 ± 6.5
BAND+PL	A_{BAND}^a	α_{BAND} (β_{BAND})	$E_{\text{p, BAND}}^b$	F_{BAND}^c	A_{PL}^d	Γ_{PL}	F_{PL}^e
090510	2.0 ± 0.2	-0.68 ± 0.06 (-3.02 ± 0.16)	3322 ± 316	241.0 ± 20.9	235.0 ± 103.0	-1.56 ± 0.05	229.0 ± 101.0

Notes.

^a Normalizations for the main components A_{BB} in units of 10^{-7} ph keV $^{-1}$ cm $^{-2}$ s $^{-1}$, and A_{CPL} and A_{BAND} in units of 10^{-2} ph keV $^{-1}$ cm $^{-2}$ s $^{-1}$.

^b Peak energy of the $E^2 dN/dE$ spectrum in units of keV.

^c Fluxes of the main components in units of 10^{-10} erg cm $^{-2}$ s $^{-1}$.

^d Normalization for the extra component in units of 10^{-7} ph keV $^{-1}$ cm $^{-2}$ s $^{-1}$.

^e Flux of the extra PL component in units of 10^{-10} erg cm $^{-2}$ s $^{-1}$.

GRBs, GRB 081024B and 081102B, are far from the best-fitting line compared with the other GRBs. Therefore, a similar linear fit is performed by excluding GRBs 081024B and 081102B. In this case, F_{main} and F_{PL} have a stronger positive correlation than that in Equation (8), with $R = 0.80$, $m = -0.50 \pm 1.55$, and $n = 1.15 \pm 0.29$, which is presented as

$$\log F_{\text{PL}} = 10^{-0.50 \pm 1.55} + (1.15 \pm 0.29) \log F_{\text{main}}, \quad (9)$$

shown in the right panel of Figure 4. In this strong positive correlation, GRBs 081024B and 081102B deviate from the correlation at about the 3σ level, with an excessively high ratio of the PL component to the main component with respect to the ratio of other GRBs. This requires an efficient conversion of the jet's kinetic energy to nonthermal particles in the prompt emission phase of the GRB or implies an important contribution from the early afterglow. In the latter case, it requires an early deceleration of the GRB jet by the interstellar medium, probably caused by a high initial bulk Lorentz factor Γ_0 for the jet given the deceleration timescale of $t_{\text{dec}} = 0.5(\eta_{\text{ISM}}/1 \text{ cm}^{-3})^{1/3} (E_k/10^{50} \text{ erg})^{1/3} (C_0/1000)^{-8/3} \text{ s}$ (Mészáros & Rees 1994).

4. Possible Origin of the Extra PL Components

In order to explore the possible origins of the extra PL components, we need to understand two main features of this spectral component, namely, the spectral slope, which is found to be approximately range between $[-2.0, -1.5]$ (see the middle panel of Figure 3) and the flux amplitude relative to that of the main spectral component (see the bottom panel of Figure 3). The origin of the extra high-energy emission (especially above 100 MeV) is still under debate. The late-time and long-lasting high-energy gamma-ray emission from GRBs, such as 080916C, 090510, and 090902B, may arise from afterglow emission rather than the

prompt emission (Kumar & Barniol Duran 2009; Ghisellini et al. 2010; Razzaque 2011). However, the high-energy emission in the early stage presents a rapid variability and a temporal correlation with the keV/MeV emission, implying an internal dissipation origin (Maxham et al. 2011; Tang et al. 2017). The origin of the extra high-energy emission, which is usually detected by Fermi-LAT in the brightest GRBs, has been explained via various high-energy processes, such as Comptonized thermal, self-synchrotron Compton (SSC) (Rees & Mészáros 1994; Asano & Inoue 2007), proton-induced cascade (Vietri 1997; Dermer & Atoyan 2006; Asano et al. 2009; Wang et al. 2018), and proton synchrotron emission (Totani 1998). Except for the one-zone model, multizone leptonic models including the SSC scenario (Corsi et al. 2010; Daigne et al. 2011), the external IC scenario (Toma et al. 2011; Peir et al. 2012), and the synchrotron radiation scenario (Loka 2010) have been invoked as well.

Generally, the extra PL component (including high-energy part) implies the presence of nonthermal relativistic particles accelerated during the prompt emission phase, which can arise when a multiplicative stochastic process (that reaches lognormal in equilibrium) is truncated before equilibrium is achieved (Mitzenmacher 2004; Reed & Jorgensen 2004; Fang et al. 2012), such as in Fermi-type acceleration processes. Here we consider two possible one-zone scenarios: one is the product of hadronic interactions of accelerated protons (the hadronic model), and the other is the IC radiation of accelerated electrons (or the leptonic model). In either scenario, the high-energy photons produced will likely be absorbed by the radiation from the main component as the GRB fireball is quite compact. The secondary electron/positron pairs will be generated and radiate a new generation of photons via the IC process in the radiation field and via the synchrotron process in the magnetic field. The new generation of photons will repeat the above process unless the energies of the newly generated

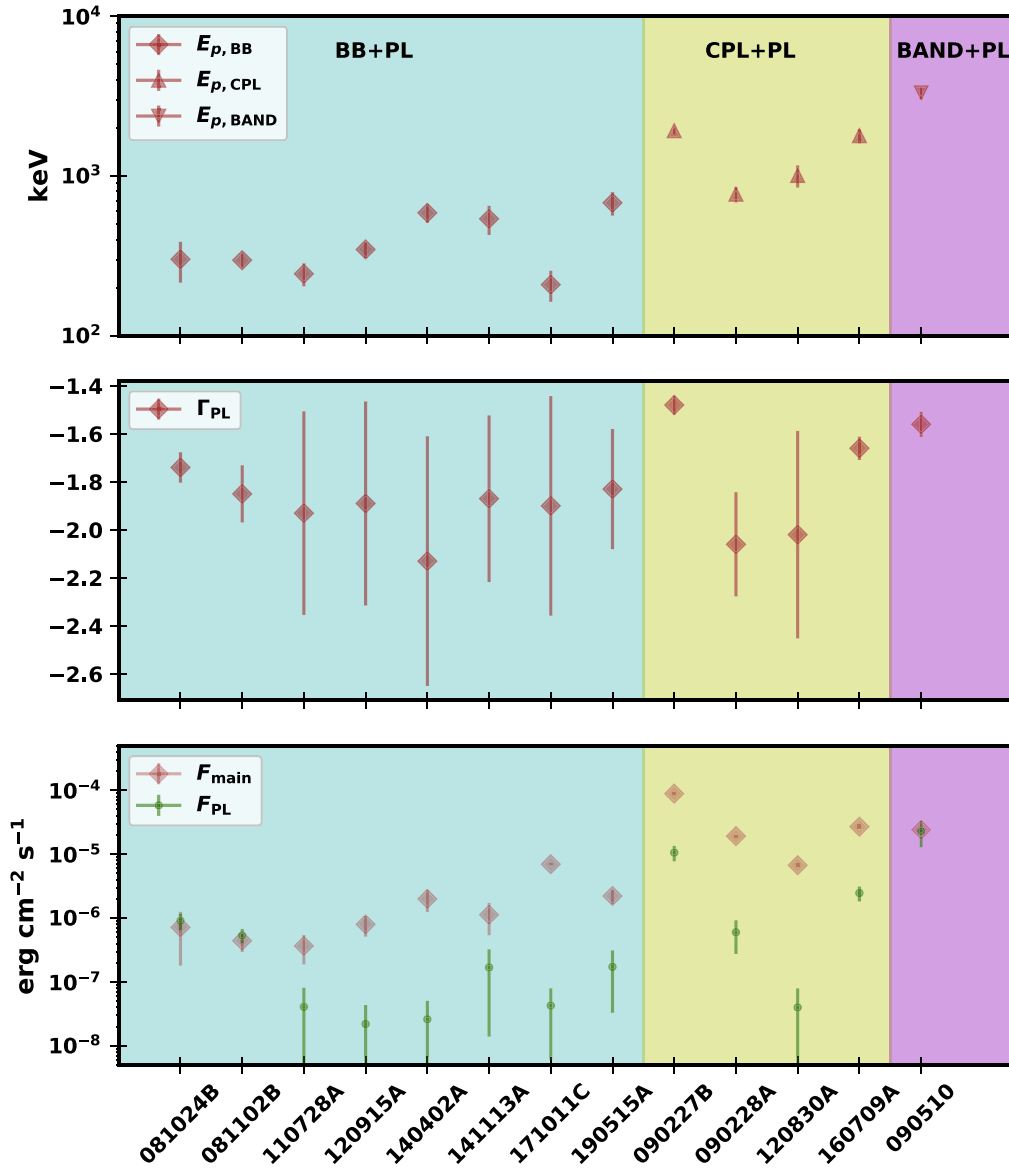


Figure 3. Top: distributions of $E_{p, BB}$, $E_{p, CPL}$ and $E_{p, BAND}$. Middle: distribution of indices of the extra PL component (Γ_{PL}). Bottom: distributions of the average flux of both components (F_{main} and F_{PL}). The cyan shading is for the class of BB+PL, the yellow shading is for the class of the CPL+PL, and the magenta shading is for the class of the BAND+PL.

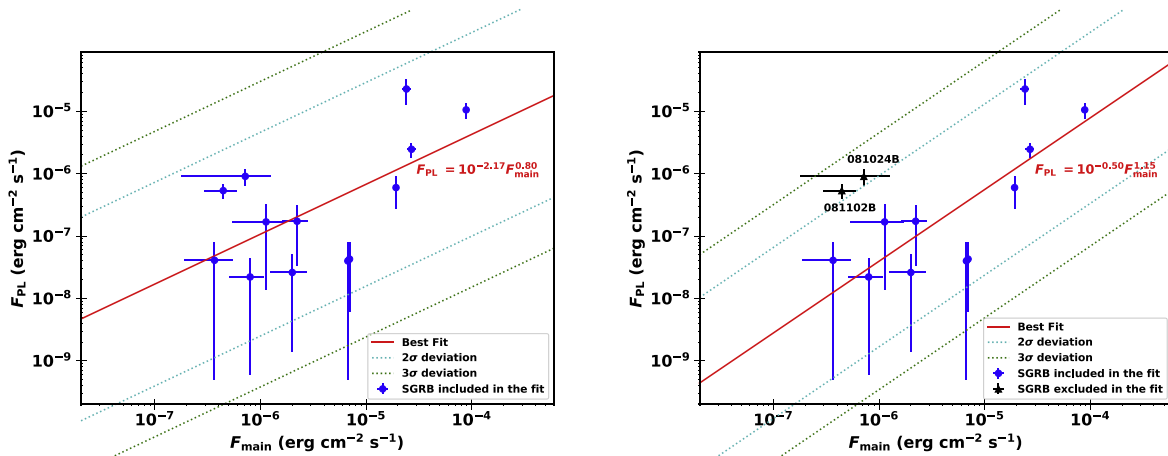


Figure 4. Left: linear fit for F_{main} and F_{PL} in the logarithm space for all GRBs in our sample. Right: linear fit for F_{main} and F_{PL} in the logarithm space excluding GRB 081024B and GRB 081102B. The solid line is the best fit and the cyan and green dotted lines represent the 2 σ and 3 σ deviations from the best fit, respectively.

photons drop below the threshold of the pair production process. Such a process is called the electromagnetic (EM) cascade. It will largely modify the spectrum of the initially generated high-energy gamma-rays and dominate the PL component. To deal with the EM cascade process, we follow the treatment described by Wang et al. (2018). Note that we do not aim to explain the main spectral component, so we simply treat it as a target photon field for $\gamma\gamma$ annihilation and IC radiation. For the main spectral component, although most of GRB prompt emission spectra around keV–MeV are present with a nonthermal shape and usually can be modeled as a smoothly broken power law, i.e., the BAND function, thermal emission originating from the photosphere is a natural prediction of the generic fireball scenario (Paczynski 1986; Shemi & Piran 1990; Mészáros et al. 1993; Pe’er et al. 2012; Hascoët et al. 2013). The relative strength of thermal emission and nonthermal emission should depend on the various environments (Daigne & Mochkovitch 2002; Ryde 2005). For the SGRB samples in this paper, the main spectral components of most of them can be described better by a BB emission. The detailed origin of the main spectral component is beyond the scope of this paper; here we only approximate it to be a BB emission in the calculation although in some GRBs the main spectral components are found to be best described with CPL or BAND.

We consider a GRB located at $z = 1$ with a bulk Lorentz factor of $\Gamma = 300$ and a dissipation radius $R = 10^4$ cm. The main spectral component is assumed to be a diluted BB distribution with a temperature of $kT = 100(1+z)$ keV and an isotropic-equivalent luminosity of $L_B = 6 \times 10^{52}$ erg s^{-1} .

For the hadronic model, the radiation at GeV energies is dominated by the EM cascade initiated by the hadronic processes including the photomeson (PM) process and the Bethe–Heitler (BH) process. Protons can be accelerated at the dissipation radius by some processes, e.g., internal shocks or magnetic reconnections. In this case, we define a magnetic equipartition coefficient (ϵ_B) as the ratio of the magnetic field energy density U_B to the photon energy density of the BB component U_{bb} , i.e., $\epsilon_B = U_B/U_{bb}$. The proton spectrum is assumed to be a PL distribution with a slope of $p = -2$ and a maximum proton energy $E_{p,max} > 0.15 \text{ GeV} \sqrt{c^2/kT} \gg 10^{17}$ eV in order to have an efficient photomeson process. The isotropic-equivalent luminosity for protons is taken to be 6×10^{53} erg s^{-1} , corresponding to a baryon loading factor of 10. The accelerated protons can generate high-energy gamma-rays and electrons through the PM and BH processes and then initiate the EM cascade in the photon field and the magnetic field. As shown in Wang et al. (2018), different values of ϵ_B can lead to different indexes of cascade emission due to the different ratios between the contributions from the synchrotron radiation and that of the IC radiation. Indeed, as we can see in the top panel of Figure 5 for a larger ϵ_B , the photon index is close to -2.0 , while for a smaller ϵ_B the photon index tends to be larger. The photon index of the cascade emission in the 1–10 keV energy range is about -1.5 in all the cases because it is mainly produced by the electrons cooled from higher energies and hence an E^{-2} spectrum is expected for these cooled electrons (Wang et al. 2018).

For the leptonic model, some electrons in the GRB fireball, in addition to those responsible for the main spectral component, are assumed to be accelerated up to ultrarelativistic energies with a PL distribution $dN/dE = AE^\alpha$. The IC

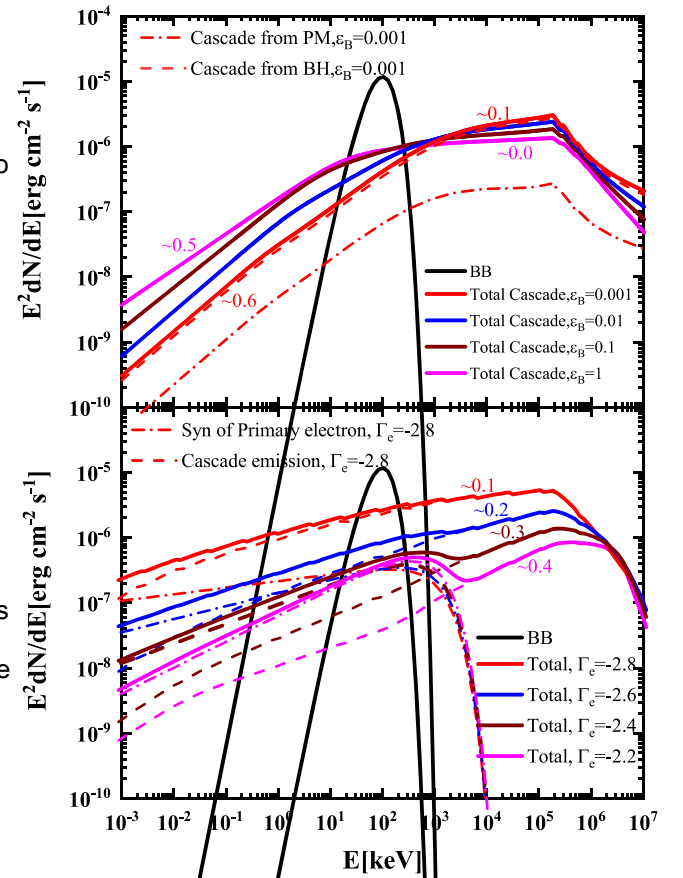


Figure 5. The extra components for the hadronic model (top) and leptonic model (bottom). In the bottom panel, the solid lines are the sum of the cascade emission (dashed lines) and the synchrotron radiation (dashed-dotted lines) of primary electrons. The approximate slopes for different lines are presented in the same colors.

scattering on both the BB component and the synchrotron radiation of these ultrarelativistic electrons themselves can give rise to high-energy radiation. Similar to that in the hadronic model, the high-energy radiation produced will trigger an EM cascade. The relative contribution from the synchrotron process and the IC process of the cascade emission depends on the equipartition coefficient ϵ_B in the same way shown in the hadronic scenario. So here we mainly explore the influence of the injection spectral index Γ_e . In the bottom panel of Figure 5 while fixing $\epsilon_B = 0.01$, the flux of synchrotron radiations of primary electrons at 100 keV and the maximum electron Lorentz factor emitting a typical photon energy of ~ 1 MeV. For $\Gamma_e = -2.8$, the spectral shape of the extra component is a quite flat PL with photon index ~ -1.9 , and for a larger Γ_e the spectra become harder with a larger photon index.

We have also checked the dependence of our results on the assumed model parameters, e.g., the temperature of the BB, which spans two orders of magnitude in Figure 3 and a background photon field with the BAND function distribution. The BAND function distribution with the typical values of the low-energy photon index $\alpha = -1.0$, the high-energy photon index $\beta = -2.2$, the peak energy $E(1+z) = 100$ keV, and the peak flux of 10^{-5} erg cm^{-2} s^{-1} , is adopted to replace the BB distribution. To explore the dependence on the different temperatures and background photon field distributions, the same electron PL distribution $dN/dE = AE^\alpha$ (the detailed origin of the BAND component is beyond the scope of the

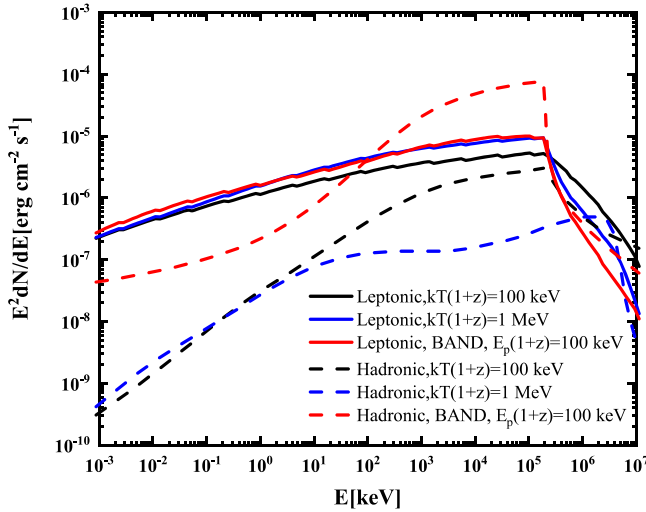


Figure 6. The effects for different background photon distributions. The hadronic model (solid lines) and the leptonic model (dashed lines) are shown with two temperatures (black and blue) for the BB background photon distribution and a BAND function (red) background photon distribution for the different temperatures of the BB component. The peak flux has the same value of $10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$. The parameters of the BAND component are $\alpha = -1.0$, $\alpha = -2.2$, and the same flux of $10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$ as the BB component. $\zeta_0 = 0.01$ and $\Gamma_e = -2.8$ are adopted for all lines. The other parameters are the same as the red lines in Figure 5 for the hadronic model and the leptonic model respectively (see text for details).

paper) and $\Gamma_e = -2.8$ are assumed for simplicity for the leptonic model, the same proton distribution as in Figure 5 is assumed for the hadronic model, and the same $\zeta_0 = 0.01$ is adopted for both models. The final cascade emission depends on whether the EM cascade is fully developed and on the total low-energy photon field including the initial photon field (BB or BAND distribution) and the cascade emission in the keV to MeV energy range. In the GRB environment, the EM cascade is likely to be fully developed due to the relatively high photon density as shown in Figure 6, for the leptonic model, different temperatures (black and blue solid lines) would produce similar radiations because the EM cascade is fully developed and the low-energy photons from keV to MeV energies are approximately dominated by the high-flux cascade emission. For the BAND function distribution as the background photon field, the cascade emission shows a similar spectral shape and the magnitude of the cascade flux depends principally on the background photon field and the adopted electron distribution. For the hadronic model in Figure 6, because the low-energy photons ranging from keV to MeV energies from the cascade emission is weaker than those from the initial BB component, the initial BB component with the same peak flux and a higher temperature provides lower photon density, inducing lower cascade emission. When a BAND function distribution is involved in the hadronic model, a higher cascade flux is expected because we fixed the flux of the BAND component to be $10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$, the same as that of the BB component, and the low-energy photon index of the BAND component, -1.0 , is much smaller than that of the BB component, so that the BAND component provides much more photons with energies below 1 keV than the BB component and makes the hadronic processes (PM and BH) more efficient, inducing a higher injection luminosity for the cascade emission. At the eV to keV energy range, the radiation becomes flat (the red dashed line in Figure 6) as the radiation below keV is mainly produced through the synchrotron radiation process by electrons from photon-photon

annihilation rather than by the electrons cooled from higher energies (the latter one usually shows a typical fast cooling photon index, i.e., ~ -1.5). The BAND function distribution provides much more target photons with energies below 1 keV and increases the photon-photon annihilation opacity. Except for the flattening at the eV-keV energy range for the BAND function in the hadronic model, the other characteristics of the spectral shapes for either the hadronic model or leptonic model at different temperatures of the BB component or even treating the background photon field as a BAND function do not change significantly compared with those in Figure 5. In addition, even when taking such flattening in the eV to keV energy range into account, the spectra for a quite large energy range extending from eV to GeV could be treated approximately as a PL component.

In summary, as shown in Figure 5, both models can produce an approximate PL component ranging from keV to GeV energies within a certain range of indices, which is consistent with our result of extra PL component for the SGRBs. However, for a flat PL component with a photon index close to -2.0 , the low-energy excess up to 10 keV could be helpful to tell us which models are preferred because for the former one the photon index of the low-energy excess is close to -1.5 while for the latter one it is $\sim (\Gamma_e - 1)/2$. Nevertheless, the poor statistics at a few keV makes it difficult to differentiate the two models with current observations. On the other hand, the cascade emissions in both models can extend down to the optical band, as shown in Figure 5, and the flux difference at the optical band between the two models becomes distinct. Therefore, in the future, observations in the optical band of the prompt emission of GRBs may tell us which model is preferable. In addition, the hadronic model usually needs to invoke a relatively larger kinetic luminosity than the leptonic model due to the lower radiation efficiency of protons than electrons and maybe also naturally predicts neutrino production, which might be constrained by the stacking observation of IceCube as it was the case in the case of LGRBs (Aartsen et al. 2015, 2016, 2017).

5. Summary and Conclusion

In this paper, we looked into the extra PL spectral components of short GRBs. By analyzing the combined Fermi-GBM and LAT data, we identified the PL component in all 13 short GRBs in our sample, including GRB 090510 and GRB 160709A, whose extra PL component was already previously reported in the literature. The average flux of the PL components within the J_0 scale positively correlates with that of the main spectral components. The slopes of the extra PL components of short GRBs are distributed in the range between -2.0 to -1.5 , which may be well reproduced by considering the EM cascade induced by ultrarelativistic protons or electrons accelerated in the prompt emission phase. In the future, observations with more statistics around the keV energy band and observations of the prompt optical GRB emission may tell us which model is preferable. In addition, the next-generation neutrino telescopes might play a key role in determining which is the preferred one of these two models.

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Facilities: Fermi-GBM, Fermi-LAT.

Software: Origin 7.0 hosted by OriginLab Corporation, 3ML (Vianello et al. 2015).

Appendix A

Comparisons of Results between the Uniform Priors (UP) Scenario and the Typical Priors (TP) Scenario

In this section, we test the uniform-distribution priors for all parameters of six models, hereafter named UP. In the UP

scenario, all normalizations (A) photon indices (α, β , and Γ), and parameters of the break energy (kT , E_c and E_p) are distributed uniformly, employing the same range as that in the typical priors (TP) scenario.

The best-fitting models are shown in Table A1. Of 13 GRBs with ΔBIC equals 0 (Best Model), 10 GRBs prefer the one-component model and 3 GRBs the two-component model. There are several candidate models with ΔBIC less than 10, which cannot be rejected by the best-model-selection method described in Section 2.4.2. Therefore, in the UP scenario, we divided the best-fitting models into the best-fitting one-component models (Best 1C Model) and the best-fitting two-component models (Best 2C Model).

Table A1
 ΔBIC and the Best-fitting Models in the UP Scenario

GRB	BB	Band	CPL	BB+PL	BAND+PL	CPL+PL	Best Model ^a	Best 1C Model ^b	Best 2C Model ^c
081024B	>10 ^d	0	7	5	>10	7	BAND	BAND	BB+PL
081102B	>10	6	0	6	>10	>10	CPL	CPL	BB+PL
090227B	>10	>10	>10	>10	7	0	CPL+PL	L	CPL+PL
090228A	>10	7	2	>10	5	0	CPL+PL	CPL	CPL+PL
090510	>10	6	>10	>10	0	>10	BAND+PL	BAND	BAND+PL
110728A	0	>10	6	8	>10	>10	BB	BB	BB+PL
120830A	>10	6	0	>10	>10	8	CPL	CPL	CPL+PL
120915A	0	>10	4	9	>10	>10	BB	BB	BB+PL
140402A	0	>10	6	7	>10	>10	BB	BB	BB+PL
141113A	0	7	1	9	>10	>10	BB	BB	BB+PL
160709A	>10	0	>10	>10	2	1	BAND	BAND	CPL+PL
171011C	0	>10	4	8	>10	>10	BB	BB	BB+PL
190515A	1	6	0	9	>10	>10	CPL	CPL	BB+PL

Notes.

^a Best-fitting model with $\Delta BIC = 0$.

^b Best-fitting model with the lowest ΔBIC among the BB, BAND, and CPL models.

^c Best-fitting model with the lowest ΔBIC among the BB+PL, BAND+PL, and CPL+PL models.

^d >10 represents the best model against this candidate model.

Table A2
Derived Parameter Values of the Best 2C Model in the UP Scenario

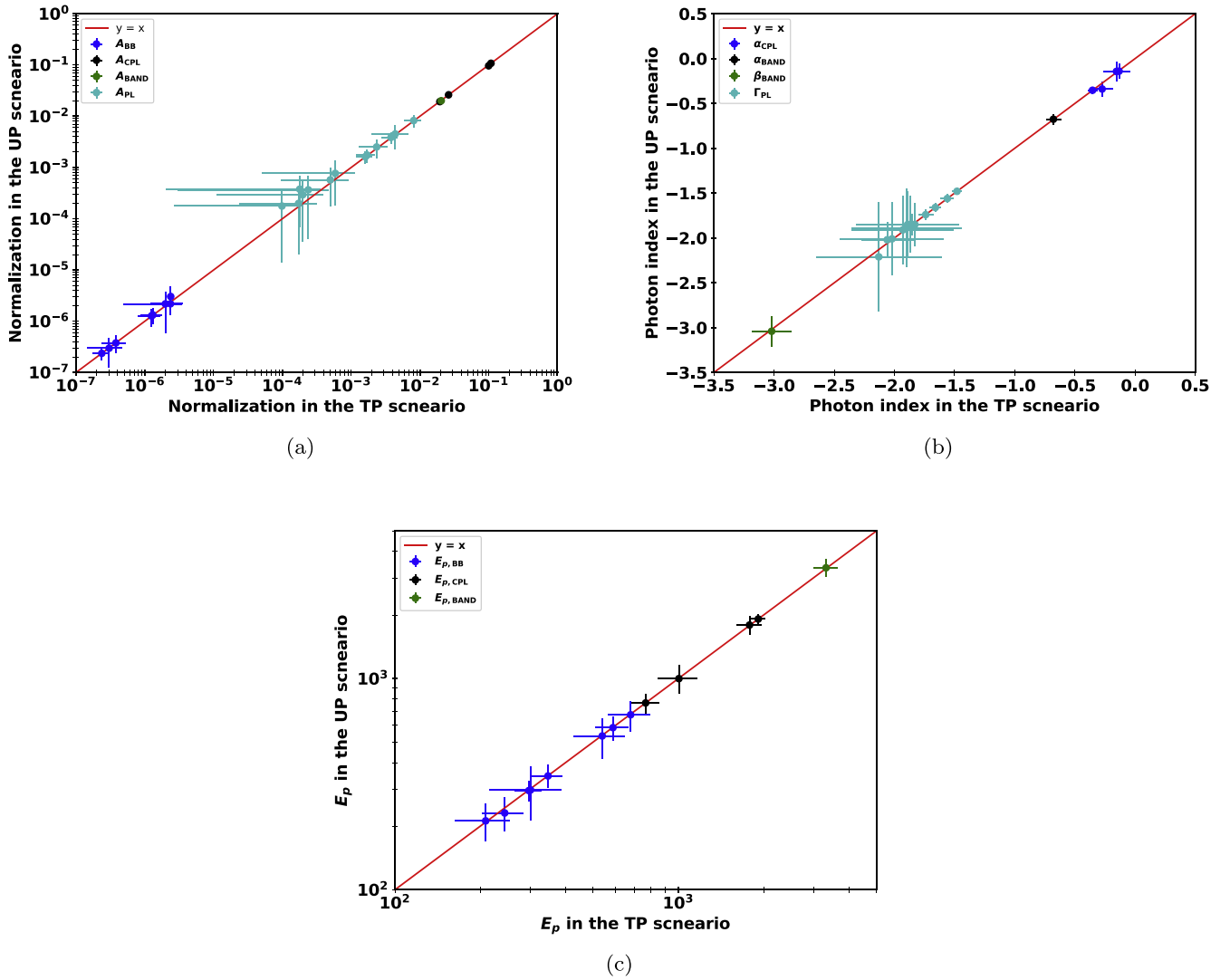
Class	Main Component	Extra PL component			
BB+PL	A_{BB}^a		$E_{p, BB}^b$	A_{PL}^c	Γ_{PL}
081024B	21.8 ± 15.9	L	297 ± 85	175.0 ± 50.1	-1.74 ± 0.06
081102B	13.3 ± 4.6	L	295 ± 32	162.0 ± 42.3	-1.85 ± 0.12
110728A	21.9 ± 16.8	L	231 ± 42	37.7 ± 30.8	-1.91 ± 0.38
120915A	12.7 ± 4.7	L	346 ± 43	17.7 ± 16.3	-1.85 ± 0.37
140402A	3.8 ± 1.4	L	586 ± 75	29.4 ± 25.8	-2.21 ± 0.61
141113A	3.0 ± 1.7	L	535 ± 116	76.8 ± 58.7	-1.85 ± 0.32
171011C	30.4 ± 17.1	L	212 ± 43	19.9 ± 17.9	-1.89 ± 0.43
190515A	2.4 ± 0.6	L	674 ± 110	57.3 ± 39.8	-1.85 ± 0.24
CPL+PL	A_{CPL}^a	α_{CPL}	$E_{p, CPL}^b$	A_{PL}^c	Γ_{PL}
090227B	10.8 ± 0.5	-0.35 ± 0.04	1915 ± 106	824.0 ± 214.0	-1.48 ± 0.04
090228A	9.6 ± 0.4	-0.34 ± 0.09	767 ± 79	452.0 ± 221.0	-2.02 ± 0.20
120830A	1.9 ± 0.1	-0.14 ± 0.11	1000 ± 155	36.7 ± 32.6	-2.01 ± 0.40
160709A	2.6 ± 0.2	-0.14 ± 0.08	1794 ± 182	386.0 ± 95.5	-1.66 ± 0.05
BAND+PL	A_{BAND}^a	α_{BAND} (β_{BAND})	$E_{p, BAND}^b$	A_{PL}^c	Γ_{PL}
090510	2.0 ± 0.2	-0.68 ± 0.06 (-3.04 ± 0.17)	3348 ± 318	252.0 ± 98.9	-1.56 ± 0.05

Notes.

^a Normalization for the main component A_{BB} in units of 10^{-7} ph keV $^{-1}$ cm $^{-2}$ s $^{-1}$, and A_{CPL} and A_{BAND} in units of 10^{-2} ph keV $^{-1}$ cm $^{-2}$ s $^{-1}$.

^b Peak energy of the $E^2 dN/dE$ spectrum in units of keV.

^c Normalization for the extra components in units of 10^0 ph keV $^{-1}$ cm $^{-2}$ s $^{-1}$.

Figure A1. Derived parameters compared between the TP and UP scenarios. The red solid line indicates $y = x$.

In order to compare results in the UP scenario with those in the TP scenario, we thus selected the Best 2C model. As shown in Table A1, the Best 2C model of each GRB in the UP scenario is the same as the best model of the corresponding GRB in the TP scenario. The resultant parameters in the Best 2C model are reported in Table A2.

After all parameters are available in both the UP scenario and the TP scenario, we thus plotted the correlations of the same parameters in two scenarios, which are shown in Figure A1. The parameters of the photon indices, the peak energies and the normalizations in both scenarios are almost lying at the equality ($y = x$) line.

In summary, the results of the best 2C models in the UP scenario are consistent with that of the best models in the TP scenario. Therefore, only the results in the TP scenario are presented in the main text.

Appendix B Spectral Energy Distributions with the Best-fitting Model for the Other 10 SGRBs

In this section, we plot the spectral energy distributions with the best-fitting model for the other 10 SGRBs in Figure B2 and Figure B3.

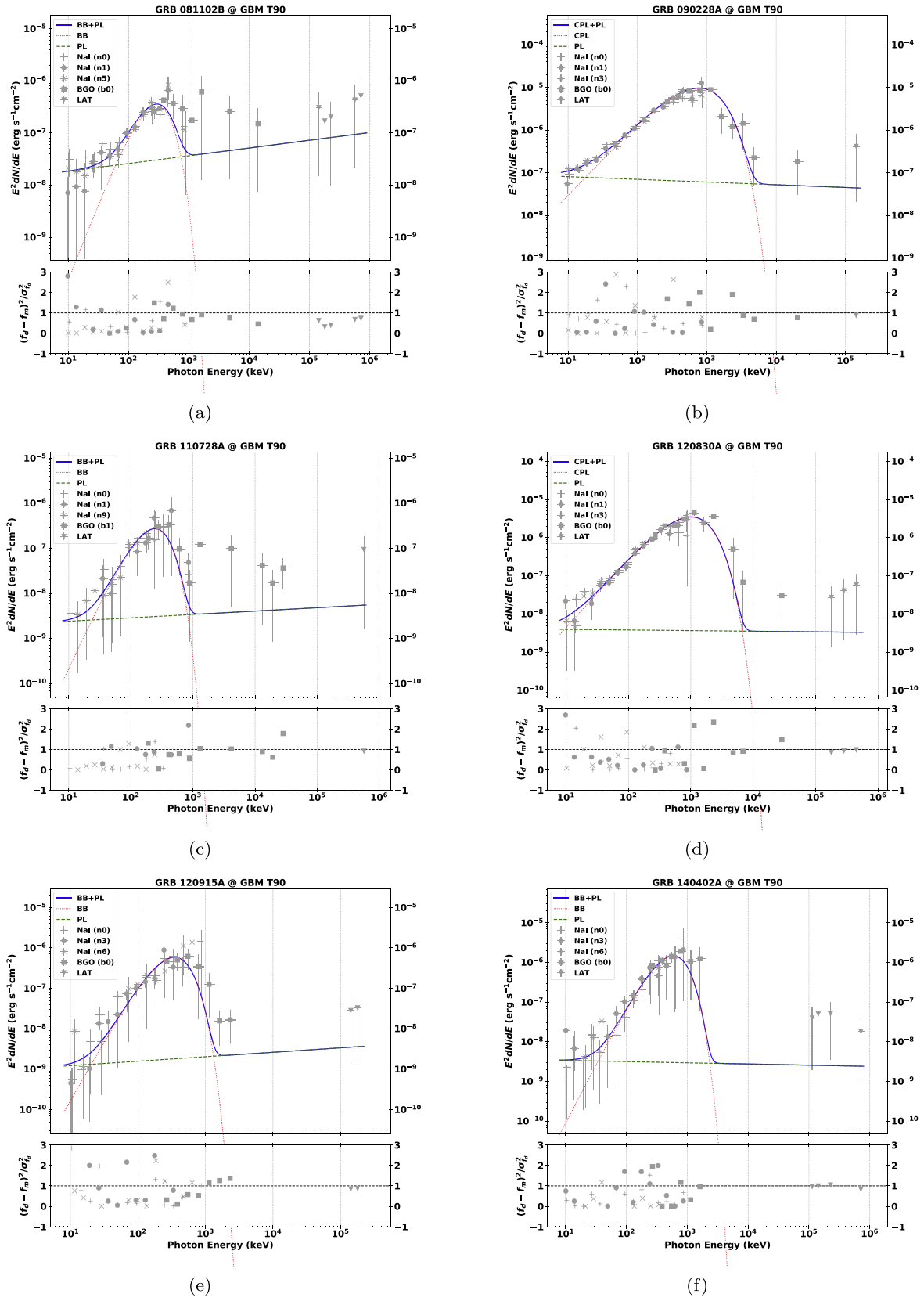
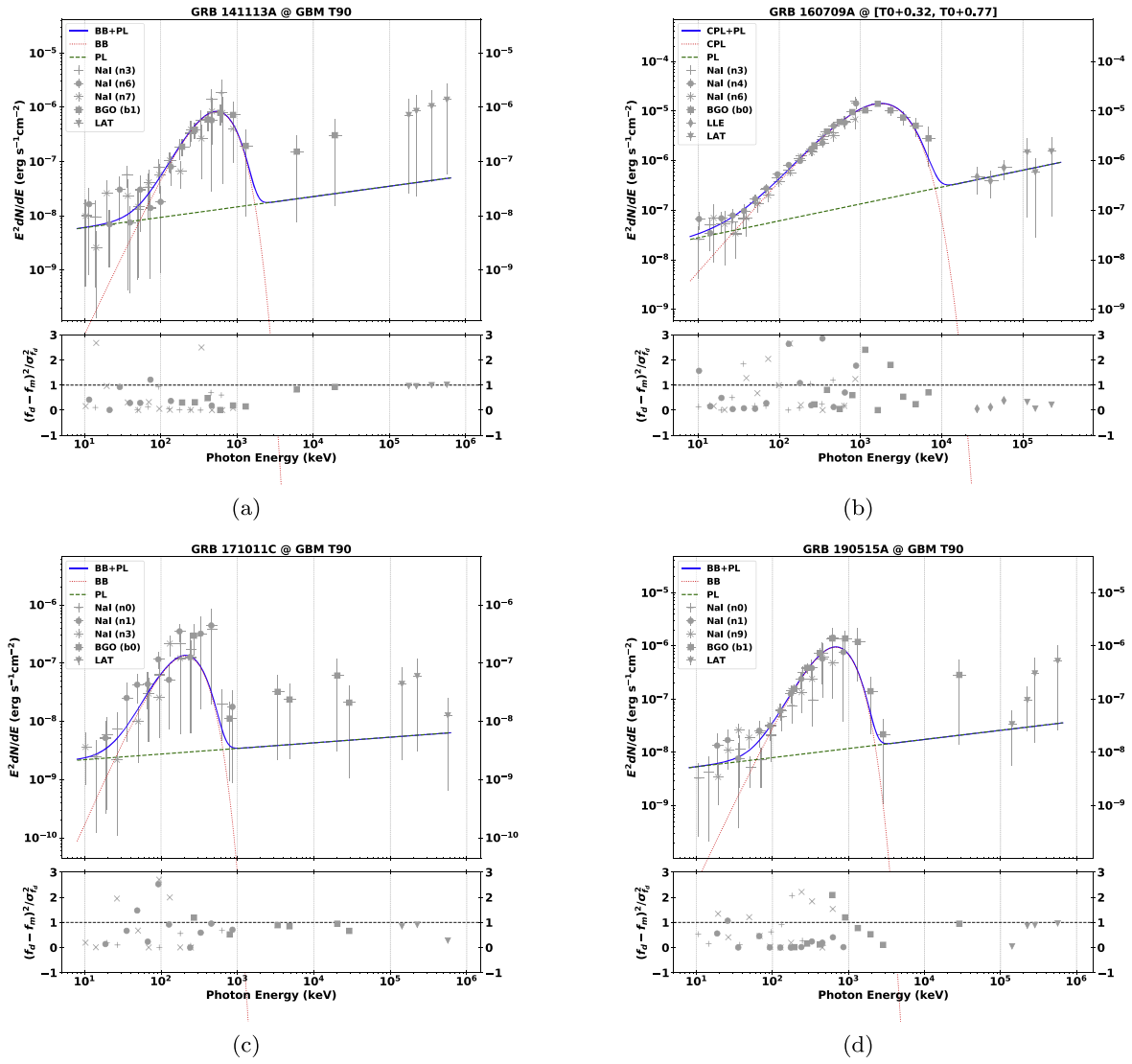


Figure B2. Same as the SEDs in Figure B, but for GRBs (a) 081102B, (b) 090228A, (c) 110728A, (d) 120830A, (e) 120915A, and (f) 140402A.



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