10-5-2018

Multicolor Blackbody Emission in GRB 081221

Shu-Jin Hou

Nanyang Normal University; Chinese Academy of Sciences; Guangxi University

Bin-Bin Zhang

Nanjing University, bbzhang@nju.edu.cn

Yan-Zhi Meng

Chinese Academy of Sciences

Xue-Feng Wu

Chinese Academy of Sciences, xfwu@pmo.ac.cn

En-Wei Liang

Guangxi University, lew@gxu.edu.cn

See next page for additional authors

Follow this and additional works at: https://digitalscholarship.unlv.edu/physastr_fac_articles

Part of the [Astrophysics and Astronomy Commons](#)

Repository Citation

Hou, S., Zhang, B., Meng, Y., Wu, X., Liang, E., Lü, H., Liu, T., Liang, Y., Lin, L., Lu, R., Huang, J., Zhang, B. (2018). Multicolor Blackbody Emission in GRB 081221. *Astrophysical Journal*, 866(1), 1-8.
<http://dx.doi.org/10.3847/1538-4357/aadc07>

This Article is protected by copyright and/or related rights. It has been brought to you by Digital Scholarship@UNLV with permission from the rights-holder(s). You are free to use this Article in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you need to obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/or on the work itself.

This Article has been accepted for inclusion in Physics & Astronomy Faculty Publications by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.

Authors

Shu-Jin Hou, Bin-Bin Zhang, Yan-Zhi Meng, Xue-Feng Wu, En-Wei Liang, Hou-Jun Lü, Tong Liu, Yun-Feng Liang, Lin Lin, Rui-jing Lu, Jin-Shu Huang, and Bing Zhang

Multicolor Blackbody Emission in GRB 081221

Shu-Jin Hou^{1,2,3,4}, Bin-Bin Zhang^{5,6}, Yan-Zhi Meng², Xue-Feng Wu², En-Wei Liang³, Hou-Jun Lü³, Tong Liu⁷,
Yun-Feng Liang², Lin Lin⁸, Rui-jing Lu³, Jin-Shu Huang^{1,4}, and Bing Zhang⁹

¹ College of Physics and Electronic Engineering, Nanyang Normal University, Nanyang, Henan 473061, People's Republic of China

² Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, People's Republic of China; xfwu@pmo.ac.cn

³ Department of Physics and GXU-NAOC Center for Astrophysics and Space Sciences, Guangxi University, Nanning 530004, People's Republic of China; lew@gxu.edu.cn

⁴ Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011; People's Republic of China

⁵ School of Astronomy and Space Science, Nanjing University, Nanjing 210093, People's Republic of China; bbzhang@nju.edu.cn

⁶ Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing, People's Republic of China

⁷ Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China

⁸ Department of Astronomy, Beijing Normal University, Beijing 100875, People's Republic of China

⁹ Department of Physics and Astronomy, University of Nevada, Las Vegas, NV 89154, USA; zhang@physics.unlv.edu

Received 2016 October 26; revised 2018 July 25; accepted 2018 August 9; published 2018 October 5

Abstract

The radiation mechanism of the prompt emission of gamma-ray bursts (GRBs) remains an open question. Although their spectra are usually well fitted with the empirical Band function, which is widely believed to be fully nonthermal and interpreted as an optically thin synchrotron emission, accumulating evidence shows that a thermal component actually exists. In this paper, a multicolor blackbody (mBB) model is proposed for the time-integrated spectrum of GRB 081221 by assuming a power-law distribution of the thermal luminosities with temperature, which manifests photospheric emissions from a different radius and/or angle. The effects of the minimum temperature $kT_{\min}$, the maximum temperature $kT_{\max}$, and the power-law index m of the luminosity distribution of an mBB are discussed. The fitting to the time-integrated spectrum during the bright phase (from 20 to 30 s since the trigger) of GRB 081221 by the mBB model yields $kT_{\min} = 4.4 \pm 0.3$ keV, $kT_{\max} = 57.0^{+1.6}_{-1.4}$ keV, and $m = -0.46^{+0.05}_{-0.06}$. When the time bin is small enough, the time-resolved spectra of GRB 081221 are well fitted with a series of single-temperature blackbodies. Our results imply the prompt emission of GRB 081221 is dominated by the photosphere emission and its time-integrated spectrum is a superposition of pure blackbody components at different times, indicating that some empirical Band spectra may be interpreted as mBB if the temperature is widely distributed.

Key words: gamma-ray burst: individual (GRB 081221) – radiation mechanisms: thermal

Supporting material: machine-readable table

1. Introduction

The prompt emission is the earliest detected signal of gamma-ray bursts (GRBs). However, its physical origin, closely related to the ejecta composition, energy dissipation, particle acceleration, and especially the radiation mechanism (e.g., Zhang 2011; Bégue & Pe'er 2015; Gao & Zhang 2015; Pe'er et al. 2015), is still a very controversial topic after more than 40 years.

Thermal emission in the relativistic fireball model is a natural explanation for the prompt emission (Goodman 1986), since the optical depth at the base of the outflow is much larger than unity and it well explains the observed small dispersion of the sub-MeV peak and high prompt emission efficiency (Mészáros & Rees 2000; Rees & Mészáros 2005). However, in the Compton GRO/BATSE era, the observed GRB spectra are well fitted by an empirical smoothly jointed broken power law, which is the so-called “Band” function (Band et al. 1993). Compared to a blackbody function, this spectrum has a much wider peak, and it is much softer at low energies. For a long time, such a spectral shape is widely believed to be produced by optically thin synchrotron processes. The Band function is then used to phenomenologically capture this shape. However, previous studies using both Compton/BASTE and *Fermi*/GBM data have shown that some observed low-energy spectra are found to be harder than that predicted by the synchrotron

model in a substantial fraction of GRBs (Preece et al. 1998; Kaneko et al. 2006; Gruber et al. 2014) and the spectral width of some GRBs is found to be very narrow (Axelsson & Borgonovo 2015; Yu et al. 2015). These facts suggest that a quasi-thermal component should exist, which has been observationally confirmed recently. The early examples include tens of BATSE GRBs (Ryde 2005; Ryde & Pe'er 2009). Thanks to *Fermi*'s unprecedented spectral energy coverage (GBM: 8 keV to 40 MeV, Meegan et al. 2009; LAT: 20 MeV to >300 GeV, Atwood et al. 2009), we now have several such examples among the *Fermi*-detected GRBs, such as GRB 090902B (Abdo et al. 2009; Ryde et al. 2010; Zhang et al. 2011), GRB 100724B (Guiriec et al. 2011), GRB 110721A (Axelsson et al. 2012), GRB 100507 (Ghirlanda et al. 2013), GRB 120323A (Guiriec et al. 2013), and GRB 101219B (Larsson et al. 2015). The thermal emission is also claimed to exist in some early X-ray flares of GRBs (Peng et al. 2014).

GRB 081221 was jointly detected by *Fermi*/GBM (Wilson-Hodge 2008), the Burst Alert Telescope (BAT) on board *Swift* (Cummings et al. 2008; Hoversten et al. 2008), and *Konus-Wind* (Golenetskii et al. 2008). The X-ray telescope on board *Swift* found the early-time X-ray afterglow (Stroh & Hoversten 2008). The faint optical and radio afterglows were also detected (Chandra & Frail 2008; Kuin & Hoversten 2008). Multi-wavelength observations of this burst provide the opportunity to explore the physical origin of the GRB. In particular, the

spectral properties of its prompt emission are similar to those of GRB 090902B (Ryde et al. 2010; Mizuta et al. 2011; Pe’er & Ryde 2011; Toma et al. 2011), showing a prominent thermal component. In this work, we perform both the time-integrated and time-resolved spectral analyses of the prompt emission of GRB 081221 to achieve this characteristic of the thermal component.

In Section 2, we give a short description of our model. The time-integrated and time-resolved spectral analyses are presented in Section 3. Conclusions are drawn in Section 4 with some discussion.

2. Multicolor Blackbody (mBB) Spectra

In the standard fireball model of GRBs, the photons produced in the outflow are thermalized, and they can escape near the photospheric radius r_{ph} , where the optical depth is equal to 1. In a relativistic, spherically symmetric wind, the photospheric radius is found to be a function of the angle to the line of sight (Abramowicz et al. 1991; Pe’er 2008; Meng et al. 2018), $r_{\text{ph}} = r_{\text{ph}}(\theta)$. This means that the observed spectrum is a superposition of a series of blackbodies of different temperature, arising from different angles to the line of sight. Furthermore, considering that photons have a finite probability of being scattered at any point in space where electrons exist, Pe’er (2008) introduced the probability density distributions for the last scattering photon positions, $P(r, \theta)$. Then, the observed spectrum is contributed by photons from the entire emitting volume, so it is certainly an mBB. Several works have tried to explain the Band function as originating from the mBB by taking into account more realistic outflow (Beloborodov 2011; Pe’er & Ryde 2011; Ito et al. 2013; Lundman et al. 2013; Deng & Zhang 2014).

The photon spectrum of a cosmological GRB with a single-temperature kT , with luminosity L_{BB} defined in the host galaxy frame and the luminosity distance D_L , can be given as

$$N(E) = \frac{15}{4\pi^5} \frac{L_{\text{BB}}}{D_L^2 (kT)^4} \frac{E^2}{e^{E/kT} - 1}. \quad (1)$$

Technically, the formula for the photon spectrum of a blackbody usually used in the spectral fitting is

$$N(E) = \frac{8.0525K}{(e^{E/kT} - 1)} \left(\frac{kT}{\text{keV}} \right)^{-4} \left(\frac{E}{\text{keV}} \right)^2, \quad (2)$$

where $N(E)$ is in units of $\text{ph cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$, and kT and E are measured in the observer’s frame. $K = L_{39}/D_{L,10\text{kpc}}^2$ is defined by the blackbody luminosity L in units of $10^{39} \text{erg s}^{-1}$ in the GRB host galaxy frame and the luminosity distance D_L in units of 10 kpc.

For mBB, different from the probability distribution of the temperature in Ryde et al. (2010), we assume that the dependence of the luminosity distribution on the temperature has a power-law form

$$\frac{dL}{dT} = \frac{m+1}{\left[\left(\frac{T_{\text{max}}}{T_{\text{min}}} \right)^{m+1} - 1 \right]} \frac{L_{\text{mBB}}}{T_{\text{min}}} \left(\frac{T}{T_{\text{min}}} \right)^m, \quad (3)$$

where m is the power-law index of the distribution, and the temperature ranges from the minimum T_{min} to the maximum T_{max} , and $L_{\text{mBB}} = \int_{T_{\text{min}}}^{T_{\text{max}}} dL$ is the total luminosity of the mBB.

Compared with the previous treatment, Equation (3) is more directly related to the physics of the GRB fireball, since it may imply the dependence of the luminosity (rather than temperature) on different radii or angles. Combining the above equations, the photon spectrum of the mBB can be formulated as

$$N(E) = \frac{8.0525(m+1)K}{\left[\left(\frac{T_{\text{max}}}{T_{\text{min}}} \right)^{m+1} - 1 \right]} \left(\frac{kT_{\text{min}}}{\text{keV}} \right)^{-2} I(E), \quad (4)$$

where

$$I(E) = \left(\frac{E}{kT_{\text{min}}} \right)^{m-1} \int_{\frac{E}{kT_{\text{max}}}}^{\frac{E}{kT_{\text{min}}}} \frac{x^{2-m}}{e^x - 1} dx, \quad (5)$$

and $x = E/kT$. Again, $N(E)$ is in units of $\text{ph cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$.

Assuming $T_{\text{min}} \ll T_{\text{max}}$ and $m < 2$, $I(E)$ can be approximated to

$$I(E) \approx \begin{cases} \frac{1}{2-m} \left(\frac{E}{kT_{\text{min}}} \right), & E \ll kT_{\text{min}} \\ \Gamma(3-m) \zeta(3-m) \left(\frac{E}{kT_{\text{min}}} \right)^{m-1}, & kT_{\text{min}} \ll E \ll kT_{\text{max}}, \\ \left(\frac{T_{\text{min}}}{T_{\text{max}}} \right)^{2-m} \left(\frac{E}{kT_{\text{min}}} \right) e^{-\frac{E}{kT_{\text{max}}}}, & kT_{\text{max}} \ll E \end{cases} \quad (6)$$

where $\Gamma(x)$ and $\zeta(x)$ are the gamma function and zeta function, respectively. The above equation shows that the low-energy ($E \ll kT_{\text{min}}$) photon spectrum follows the Rayleigh–Jeans law of $N(E) \propto E$, while the high-energy ($E \gg kT_{\text{max}}$) spectrum behaves as a power law with an exponential cutoff. For the middle regime of the spectrum ($kT_{\text{min}} < E < kT_{\text{max}}$), different m corresponds to different shape. We can see that $m \leq 2$ is required. Otherwise, the photon spectrum $N(E) \propto E^{m-1}$ in the energy band of $kT_{\text{min}} < E < kT_{\text{max}}$ is harder than the blackbody $N(E) \propto E$, which is physically unrealistic. In fact, for $m > 2$, $N(E)$ is always proportional to E for $E < kT_{\text{max}}$, as in this case the whole spectrum is dominated by the $T = T_{\text{max}}$ blackbody. Thus, compared with Ryde et al. (2010), by considering the effect of T_{min} , we obtain the complete mBB spectrum including the Rayleigh–Jeans component ($E < kT_{\text{min}}$).

In Figure 1, we plot the mBB spectra for different m values. $kT_{\text{min}} = 1 \text{ keV}$ and $kT_{\text{max}} = 100 \text{ keV}$ are assumed. For $m = 2$, the spectrum is similar to a pure blackbody. In the $E^2 N(E)$ spectrum, however, it deviates from the pure blackbody by a factor of $\ln(kT_{\text{max}}/E)$ from kT_{min} to kT_{max} . Note that for $m = 2$ the low-energy spectrum of $E < 3kT_{\text{min}}$ is influenced by the entire blackbody components with temperatures from kT_{min} to kT_{max} , while the low-energy spectrum is mainly dominated by the blackbody component with temperature $\sim kT_{\text{min}}$ for $m < 2$, which explains a higher $E^2 N(E)$ for the $m = 2$ case. The spectrum in the case of $m = 1$ can nicely explain the observed narrowly shaped spectrum of GRB 090902B. For $m = 0$, it is the same as the Comptonized spectrum, which is also known as the COMPTEL model (Goldstein et al. 2012). As for GRB 081221 analyzed in the next section, the spectrum ($m = -0.46$) is between the two cases of $m = 0$ and $m = -1$. If the

Figure 1. Examples of the mBB spectra for different m . $kT_{\min} = 1$ keV and $kT_{\max} = 100$ keV are assumed. Black solid lines are plotted with analytical approximations (Equation (6)), while the other lines are exact numerical calculations with Equation (4).

Figure 2. GBM light curves of GRB 081221 (top two panels) and the spectral evolution (bottom two panels).

minimum and maximum temperatures are close enough, i.e., $T_{\min} \sim T_{\max}$, the spectrum returns to the pure blackbody. On the other hand, if the minimum temperature $T_{\min}$ is below the energy band of the GRB detector, the low-energy part of the mBB spectrum cannot be observed, and the middle- and the high-energy parts might be approximated as the well-known Band spectrum or the Comptonized cutoff power-law spectrum in a limited energy band determined by the detector. In this paper, we only consider the case of a single power-law distribution of the blackbody temperature. The temperature distribution of more realistic GRB fireballs may be much more complicated.

3. Spectral Analysis of GRB 081221

GRB 081221 at redshift $z = 2.26$ (Salvaterra et al. 2012), a bright GRB with separable pulses, was detected by *Fermi*/GBM, *Swift*/BAT, and *Konus/Wind*. There was no detection in the LAT band. We analyze the GBM data using the same method as described in Zhang et al. (2011) and fit the extracted

spectra with the McSpecFit package (Zhang et al. 2016). We selected the data from GBM detectors NaI 1, NaI 2, and BGO 0, according to their geometry relative to the GRB position. The light curve with a duration of about 40 s consists of a weak initial peak (precursor) and a bright second peak (main burst), as can be seen in Figure 2. The duration of the precursor is about 5 s, and the quasi-quietest time is ~ 10 s between these two peaks. The main burst consists of three overlapping pulses with a duration of ~ 20 s (Cummings et al. 2008; Golenetskii et al. 2008; Wilson-Hodge 2008). The event fluence of GRB 081221 is $(3.7 \pm 0.1) \times 10^{-5}$ erg cm $^{-2}$ (8–1000 keV), and the isotropic energy is $(4.21 \pm 0.42) \times 10^{52}$ erg.

We perform the time-resolved spectral analysis of GRB 081221 using the GBM data. We use the personal IDL code library ZBBIDL and personal Python library ZBBPY in the whole data processing project developed and applied in Zhang et al. (2018). Dividing the whole burst into 40 slices at first, we used a single-blackbody (BB) model and an mBB model to fit the data, respectively. The fitting results are presented in Table 1. The Bayesian information criterion (BIC) is a tool for model selection (Schwarz 1978; Wei et al. 2016). A model is preferred when it has the lower BIC value than the other. We define $\Delta\text{BIC} = \text{BIC}_1 - \text{BIC}_2$, where BIC_i corresponds to Model i ($i = 1, 2$). If ΔBIC is from 2 to 6, the preference for Model 2 is positive; if ΔBIC is from 6 to 10, the preference for Model 2 is strong; and if ΔBIC is above 10, the preference for Model 2 is very strong. By comparing their BIC, we come to the conclusion that although the BB model is not the best-fit model, we can use this model to explore the physical properties of the GRB photosphere, and the BB model can be reasonably used to fit the data (Zhang et al. 2018). We also find that the weaker the radiation is, the more suitable the single-blackbody model is. This means that the time slice with high fluence may be superimposed by a number of the BB components. The spectral evolution may be another important reason. We are then motivated to take a smaller time bin. Thanks to the high flux of this burst, we divide the burst into 250 slices based on the criterion that there are at least 20 net counts in at least 10 energy channels in the spectrum to conduct a fine-time-resolved spectral analysis. The two blackbodies plus a power-law model (2BBPL), which was applied to GRB 081221 by Basak & Rao (2013), is also considered in this work. The computed BIC for the time-resolved spectra of GRB 081221 with these three models is listed in Table 2. The evolution diagram of the ΔBIC with time and histogram about $\Delta\text{BIC}_{\text{mBB-BB}}$ and $\Delta\text{BIC}_{\text{2BBPL-BB}}$ are shown in Figure 3. The ΔBIC of most time intervals is larger than 10, so it can be judged that the single-blackbody model is the best-fit model. Comparing the BIC values of the BB model in the Tables 1 and 2, we also find that the smaller the interval is, the more acceptable the single-blackbody model is. This means that the whole radiation is superimposed with blackbodies of different temperatures and the spectral evolution has a great influence on the time-integrated spectrum. The temporal evolution of kT is shown in Figure 2. The kT of the precursor evolves quickly from ~ 30 to ~ 7 keV. In the main part of the burst, kT increases rapidly from ~ 9 to ~ 20 keV, then decreases with the flux.

The left panel of Figure 4 shows an example of a spectral fitting with a BB model in the interval of [19.5, 20.0 s], when the prompt emission is around the brightest peak, where we obtained $kT = 19.9 \pm 0.5$ keV. We noted that the non-Gaussian pattern of the residuals indicates that the spectral

Table 1
The Fitting Results of the Time-resolved Spectra of GRB 081221 with the BB Model and the mBB Model

Time (s)	A_1	kT (keV)	PGSTAT/dof	BIC	A_2	$kT_{\min}$ (keV)	$kT_{\max}$ (keV)	m	PGSTAT/dof	BIC
(0.00, 2.00)	$0.69^{+0.03}_{-0.03}$	$30.72^{+1.64}_{-1.48}$	388.85/364	400.65	$2.03^{+2.16}_{-0.21}$	$3.74^{+5.13}_{-0.36}$	$79.32^{+26.08}_{-3.58}$	$0.25^{+0.05}_{-0.54}$	336.88/362	360.49
(2.00, 4.00)	$0.65^{+0.02}_{-0.02}$	$16.44^{+0.66}_{-0.56}$	398.35/364	410.15	$3.56^{+0.66}_{-0.82}$	$5.64^{+1.78}_{-1.61}$	$54.88^{+17.04}_{-7.88}$	$-0.65^{+0.39}_{-0.43}$	308.02/362	331.63
(4.00, 6.00)	$0.43^{+0.02}_{-0.03}$	$11.61^{+0.64}_{-0.56}$	365.33/364	377.12	$3.70^{+0.40}_{-0.08}$	$5.84^{+1.14}_{-0.24}$	$46.49^{+346.38}_{-13.07}$	$-1.31^{+0.18}_{-0.18}$	302.36/362	325.98
(6.00, 8.00)	$0.24^{+0.03}_{-0.03}$	$9.65^{+0.73}_{-0.63}$	344.54/364	356.34	$3.47^{+0.31}_{-0.28}$	$5.49^{+0.86}_{-0.68}$	$364.53^{+493.58}_{-142.56}$	$-1.54^{+0.17}_{-0.29}$	313.94/362	337.55
(8.00, 10.00)	$0.29^{+0.03}_{-0.03}$	$10.21^{+0.64}_{-0.53}$	299.41/364	311.20	$3.01^{+0.34}_{-0.34}$	$4.42^{+0.85}_{-0.85}$	$36.11^{+338.91}_{-16.54}$	$-1.16^{+0.23}_{-0.23}$	267.90/362	291.51
(10.00, 12.00)	$0.14^{+0.03}_{-0.03}$	$7.16^{+0.53}_{-0.46}$	332.47/364	344.27	$3.03^{+0.14}_{-0.49}$	$4.36^{+0.35}_{-0.96}$	$106.22^{+345.39}_{-99.35}$	$-1.81^{+0.29}_{-0.11}$	317.17/362	340.78
(12.00, 14.00)	$0.21^{+0.03}_{-0.03}$	$9.80^{+0.84}_{-0.65}$	328.09/364	339.89	$2.91^{+0.47}_{-0.53}$	$4.33^{+1.08}_{-0.96}$	$157.80^{+331.54}_{-118.79}$	$-1.19^{+0.15}_{-0.24}$	284.23/362	307.84
(14.00, 16.00)	$0.50^{+0.02}_{-0.02}$	$10.21^{+0.44}_{-0.42}$	350.09/364	361.89	$2.07^{+0.36}_{-0.36}$	$2.62^{+0.76}_{-0.76}$	$33.91^{+378.53}_{-7.64}$	$-0.73^{+0.21}_{-0.21}$	267.42/362	291.04
(16.00, 17.00)	$0.44^{+0.03}_{-0.03}$	$9.02^{+0.72}_{-0.66}$	370.33/364	382.13	$2.83^{+0.58}_{-0.23}$	$3.58^{+1.17}_{-0.36}$	$64.27^{+366.77}_{-34.99}$	$-1.29^{+0.09}_{-0.30}$	317.60/362	341.21
(17.00, 18.00)	$0.83^{+0.02}_{-0.02}$	$15.35^{+0.54}_{-0.53}$	478.32/364	490.12	$1.39^{+1.70}_{-0.02}$	$1.87^{+2.14}_{-0.02}$	$52.40^{+11.31}_{-2.74}$	$-0.33^{+0.01}_{-0.32}$	317.05/362	340.66
(18.00, 18.50)	$1.16^{+0.02}_{-0.02}$	$19.99^{+0.66}_{-0.55}$	329.25/364	341.05	$1.17^{+1.22}_{-0.39}$	$1.98^{+2.28}_{-0.24}$	$44.59^{+12.58}_{-1.20}$	$0.42^{+0.37}_{-0.37}$	261.68/362	285.29
(18.50, 19.00)	$1.26^{+0.02}_{-0.02}$	$20.63^{+0.58}_{-0.56}$	370.22/364	382.02	$3.61^{+1.03}_{-0.02}$	$5.01^{+2.52}_{-0.04}$	$55.19^{+8.85}_{-2.83}$	$-0.06^{+0.06}_{-0.45}$	260.35/362	283.96
(19.00, 19.50)	$1.28^{+0.01}_{-0.02}$	$21.29^{+0.60}_{-0.52}$	361.55/364	373.35	$3.15^{+0.88}_{-0.58}$	$4.33^{+2.27}_{-1.56}$	$50.38^{+14.88}_{-4.45}$	$0.30^{+0.38}_{-0.45}$	262.67/362	286.28
(19.50, 20.00)	$1.24^{+0.02}_{-0.02}$	$19.93^{+0.52}_{-0.50}$	314.17/364	325.97	$2.97^{+0.92}_{-0.80}$	$4.12^{+2.42}_{-1.19}$	$38.11^{+8.36}_{-7.12}$	$0.61^{+0.38}_{-0.67}$	245.89/362	269.50
(20.00, 20.50)	$1.27^{+0.02}_{-0.02}$	$20.09^{+0.57}_{-0.51}$	397.53/364	409.32	$3.36^{+1.03}_{-0.67}$	$4.46^{+2.29}_{-1.06}$	$54.78^{+7.30}_{-4.99}$	$-0.04^{+0.18}_{-0.40}$	269.52/362	293.13
(20.50, 21.00)	$1.33^{+0.01}_{-0.01}$	$21.47^{+0.54}_{-0.57}$	473.93/364	485.73	$2.97^{+0.62}_{-0.11}$	$3.80^{+1.41}_{-0.18}$	$55.92^{+12.07}_{-0.64}$	$0.14^{+0.26}_{-0.26}$	314.18/362	337.79
(21.00, 21.50)	$1.43^{+0.01}_{-0.01}$	$22.38^{+0.51}_{-0.46}$	405.52/364	417.32	$2.46^{+0.80}_{-0.21}$	$3.18^{+1.55}_{-0.39}$	$48.25^{+5.50}_{-5.50}$	$0.48^{+0.26}_{-0.26}$	254.51/362	278.12
(21.50, 22.00)	$1.42^{+0.01}_{-0.01}$	$21.35^{+0.48}_{-0.41}$	384.52/364	396.32	$2.30^{+0.91}_{-0.18}$	$3.05^{+1.93}_{-0.18}$	$40.79^{+9.23}_{-1.35}$	$0.70^{+0.26}_{-0.32}$	284.85/362	308.46
(22.00, 22.50)	$1.32^{+0.01}_{-0.01}$	$19.44^{+0.41}_{-0.45}$	421.93/364	433.73	$2.75^{+1.83}_{-0.35}$	$3.40^{+3.62}_{-0.35}$	$48.13^{+11.45}_{-2.12}$	$0.14^{+0.06}_{-0.70}$	268.20/362	291.81
(22.50, 23.00)	$1.22^{+0.01}_{-0.02}$	$18.53^{+0.57}_{-0.48}$	348.99/364	360.79	$1.60^{+1.03}_{-0.71}$	$2.13^{+1.58}_{-0.58}$	$46.69^{+9.11}_{-1.62}$	$0.17^{+0.02}_{-0.50}$	234.22/362	257.83
(23.00, 23.50)	$1.18^{+0.02}_{-0.02}$	$16.54^{+0.53}_{-0.49}$	389.35/364	401.15	$4.35^{+0.31}_{-0.45}$	$6.29^{+0.87}_{-1.10}$	$63.59^{+8.37}_{-6.73}$	$-0.82^{+0.21}_{-0.21}$	218.00/362	241.61
(23.50, 24.00)	$1.26^{+0.01}_{-0.01}$	$18.46^{+0.54}_{-0.46}$	412.20/364	424.00	$3.06^{+1.14}_{-0.16}$	$3.79^{+2.23}_{-0.26}$	$53.81^{+10.00}_{-2.11}$	$-0.12^{+0.03}_{-0.41}$	256.61/362	280.22
(24.00, 24.50)	$1.36^{+0.01}_{-0.01}$	$20.43^{+0.49}_{-0.50}$	414.72/364	426.52	$3.47^{+0.86}_{-1.08}$	$4.51^{+1.86}_{-1.58}$	$55.93^{+6.89}_{-5.05}$	$-0.05^{+0.23}_{-0.33}$	238.71/362	262.32
(24.50, 25.00)	$1.28^{+0.01}_{-0.02}$	$17.85^{+0.45}_{-0.42}$	435.96/364	447.76	$4.05^{+0.45}_{-0.65}$	$5.53^{+1.12}_{-1.30}$	$55.18^{+6.54}_{-4.96}$	$-0.47^{+0.26}_{-0.24}$	262.46/362	286.07
(25.00, 25.50)	$1.16^{+0.02}_{-0.02}$	$15.16^{+0.47}_{-0.40}$	434.11/364	445.91	$2.30^{+1.25}_{-0.63}$	$2.51^{+1.84}_{-0.62}$	$47.81^{+6.95}_{-3.07}$	$-0.35^{+0.09}_{-0.30}$	268.31/362	291.92
(25.50, 26.00)	$1.16^{+0.01}_{-0.02}$	$14.18^{+0.39}_{-0.41}$	360.71/364	372.51	$1.80^{+0.80}_{-0.23}$	$2.09^{+1.17}_{-0.26}$	$36.18^{+6.04}_{-1.69}$	$-0.07^{+0.02}_{-0.54}$	241.03/362	264.64
(26.00, 26.50)	$1.15^{+0.02}_{-0.02}$	$13.20^{+0.40}_{-0.36}$	390.14/364	401.94	$4.47^{+0.45}_{-0.19}$	$6.27^{+1.31}_{-0.49}$	$51.84^{+190.77}_{-3.05}$	$-1.19^{+0.11}_{-0.44}$	254.73/362	278.34
(26.50, 27.00)	$1.15^{+0.01}_{-0.01}$	$13.18^{+0.33}_{-0.36}$	417.67/364	429.47	$1.83^{+1.60}_{-0.02}$	$2.02^{+1.98}_{-0.04}$	$35.13^{+5.61}_{-1.29}$	$-0.20^{+0.02}_{-0.43}$	278.27/362	301.88
(27.00, 27.50)	$1.16^{+0.01}_{-0.02}$	$12.86^{+0.40}_{-0.35}$	406.79/364	418.59	$4.38^{+0.35}_{-0.33}$	$5.93^{+0.99}_{-0.77}$	$55.82^{+17.44}_{-6.50}$	$-1.21^{+0.22}_{-0.26}$	250.26/362	273.88
(27.50, 28.00)	$1.13^{+0.02}_{-0.02}$	$13.33^{+0.46}_{-0.43}$	452.96/364	464.75	$3.58^{+0.41}_{-0.66}$	$4.24^{+0.84}_{-1.07}$	$55.57^{+8.64}_{-6.24}$	$-0.85^{+0.22}_{-0.18}$	252.09/362	275.70
(28.00, 28.50)	$1.09^{+0.02}_{-0.02}$	$12.98^{+0.45}_{-0.41}$	417.06/364	428.86	$3.63^{+0.51}_{-0.38}$	$4.39^{+1.09}_{-0.69}$	$53.55^{+12.81}_{-4.45}$	$-0.87^{+0.14}_{-0.27}$	253.16/362	276.77
(28.50, 29.00)	$1.08^{+0.02}_{-0.02}$	$13.19^{+0.49}_{-0.48}$	396.99/364	408.79	$3.38^{+0.59}_{-0.38}$	$3.96^{+1.14}_{-0.59}$	$50.39^{+10.44}_{-4.12}$	$-0.77^{+0.13}_{-0.27}$	235.18/362	258.79
(29.00, 29.50)	$1.03^{+0.02}_{-0.02}$	$13.20^{+0.52}_{-0.52}$	398.43/364	410.24	$3.44^{+0.50}_{-0.45}$	$4.13^{+1.04}_{-0.83}$	$62.45^{+15.85}_{-6.83}$	$-0.86^{+0.14}_{-0.21}$	232.75/362	256.36
(29.50, 30.00)	$1.01^{+0.02}_{-0.02}$	$12.45^{+0.53}_{-0.46}$	362.23/364	374.04	$3.61^{+0.51}_{-0.49}$	$4.47^{+1.08}_{-0.86}$	$46.57^{+10.44}_{-5.27}$	$-0.91^{+0.19}_{-0.32}$	245.11/362	268.72
(30.00, 30.50)	$0.97^{+0.02}_{-0.02}$	$12.58^{+0.49}_{-0.48}$	335.44/364	347.24	$3.56^{+0.72}_{-0.50}$	$4.44^{+1.64}_{-0.87}$	$52.72^{+46.95}_{-8.14}$	$-0.94^{+0.24}_{-0.43}$	233.09/362	256.70
(30.50, 31.00)	$0.91^{+0.02}_{-0.02}$	$11.69^{+0.58}_{-0.54}$	376.28/364	388.08	$3.61^{+0.67}_{-0.15}$	$4.55^{+1.58}_{-0.30}$	$56.60^{+405.12}_{-3.49}$	$-1.07^{+0.06}_{-0.44}$	276.00/362	299.61
(31.00, 31.50)	$0.86^{+0.02}_{-0.02}$	$11.57^{+0.55}_{-0.51}$	283.93/364	295.73	$3.94^{+0.60}_{-0.01}$	$5.39^{+1.63}_{-0.08}$	$43.76^{+369.45}_{-15.08}$	$-1.22^{+0.24}_{-0.24}$	228.62/362	252.23
(31.50, 33.60)	$0.74^{+0.01}_{-0.01}$	$11.30^{+0.33}_{-0.34}$	382.33/364	394.13	$3.04^{+1.06}_{-0.45}$	$3.86^{+2.19}_{-0.65}$	$35.49^{+20.33}_{-1.99}$	$-0.77^{+0.18}_{-0.75}$	271.64/362	295.25
(33.60, 35.20)	$0.54^{+0.02}_{-0.02}$	$9.78^{+0.41}_{-0.42}$	383.78/364	395.58	$3.35^{+0.23}_{-0.23}$	$4.53^{+0.59}_{-0.59}$	$38.59^{+378.53}_{-11.83}$	$-1.29^{+0.17}_{-0.17}$	312.56/362	336.17
(35.20, 40.00)	$0.27^{+0.02}_{-0.02}$	$8.99^{+0.34}_{-0.31}$	340.80/364	352.60	$3.64^{+0.05}_{-0.26}$	$5.76^{+0.15}_{-0.68}$	$849.34^{+150.64}_{-317.78}$	$-1.92^{+0.21}_{-0.03}$	297.39/362	321.00

evolution may still exist even within such a small time interval. Furthermore, the right panel of Figure 4 shows the flux- kT correlation for the time-resolved spectra; a higher flux generally corresponds to a BB component with a higher temperature (Golenetskii et al. 1983; Kargatis et al. 1994; Boronovo & Ryde 2001; Fan et al. 2012). This is similar to the E_p -flux correlation in the Band model fittings (Lu et al. 2010). We fit the flux- kT data with a power law for the decay phase of the second pulse ($t > 30$ s) and the time interval of 12–40 s. The slopes are ~ 4.1 and ~ 2.7 , respectively. For the decay phase of the second pulse, this slope is consistent with the BB model prediction. For a BB, the luminosity of the photospheric emission is $L = 16\pi R^2 \frac{(1+z)^4}{\Gamma^2} \sigma T^4$, where R is the photospheric radius and Γ is the Lorentz factor. The luminosity is less sensitive to the radius ($\propto R^2$) and the Lorentz factor ($\propto \Gamma^{-2}$) than to the temperature ($\propto T^4$), so it is expected that the flux is

approximately proportional to T^4 . The deviation of the observed dependence of the BB flux on temperature ($T^{2.7}$) during the time interval of 12–40 s to the theoretical T^4 should be attributed to some mild temporal evolution of the photosphere radius and/or the Lorentz factor, as this time interval corresponds to the whole period of the main burst of GRB 081221, which consists of the rising, peak, and decaying parts. Note that the slopes of 4.1 and 2.7 here are irrelevant to the power-law index m in Equation (3).

The model fittings to the time-integrated GBM spectrum between 20 and 30 s of GRB 081221 are shown in Figure 5. Two spectral breaks at ~ 15 and ~ 180 keV are seen in this figure. The spectrum rises fast below ~ 15 keV, then shows a plateau segment between ~ 15 and ~ 180 keV, and finally follows a steep decrease above ~ 180 keV. The fitting results are presented in Table 3. Parameter constraints of the mBB model and Band function model for the time-integrated spectrum between 20 and

Figure 3. Evolution of the ΔBIC with time for the three models (left panel) and histogram of the ΔBIC (right panel).

Figure 4. Left: the time-resolved photon spectrum when the flux is around the highest peak (time from 19.5 to 20.0 s since the trigger), in which a blackbody model is applied. Right: evolution of kT vs. flux. The red points and green solid line indicate the data and the flux $\propto (kT)^{4.1}$ correlation in the decay phase of the second (main) pulse ($t > 30$ s). The blue solid line indicates the flux $\propto (kT)^{2.7}$ for the whole period of the second (main) pulse ($t = 12\text{--}40$ s).

30 s are shown in Figure 6. We find that the mBB model ($m = -0.46$) can fit almost as well as the Band model, which means that the Band spectrum in GRB 081221 can be well interpreted as the mBB. The derived minimum and maximum temperatures for the time-integrated spectrum are $kT_{\min} = 4.4 \pm 0.3$ keV and $kT_{\max} = 57.0^{+1.6}_{-1.4}$ keV, respectively. The derived single-blackbody temperatures range from $12.45^{+0.53}_{-0.46}$ to $22.38^{+0.51}_{-0.46}$ keV. This difference can be understood by the following factors: (1) Different formulation. $T_{\min}$ and $T_{\max}$ can be regarded as effective temperatures that are not exactly the term of the temperature kT in the BB model. (2) Different selection of data. The first approach is applied to the whole time-integrated spectra while the second approach is applied to each slice of the time-resolved spectra, so $T_{\min}$ and $T_{\max}$ in mBB are “averaged” values and are subject to spectral evolution. Thus, they are not necessarily exactly the same as kT in the BB model.

Based on the above spectral analysis, we find that the prompt emission of GRB 081221 may be overwhelmed by the photospheric (thermal) emission, without any significant nonthermal contribution in the GBM energy band.

4. Discussion and Conclusions

Usually, the spectrum of thermal emission from astronomical objects can be described by the Planck function. However, for GRBs that are widely believed to have a relativistic outflow, due to the angle dependence of the photospheric emission together with the Doppler boosting effect (Pe’er 2008), the photospheric emission should be a superposition of blackbodies of different temperatures, which is also called the mBB.

We note that Ryde et al. (2010) and Larsson et al. (2011) used a broadened photospheric component based on an mBB model and the XSPEC model diskbb to fit the spectra of GRB 090902B and GRB 061007, respectively. In their works, they adopted $T_{\min} \simeq 0$ as $T_{\min} \ll T_{\max}$ and $kT_{\min}$ below the lowest energy of the energy band of the detector in their cases. In the diskbb model, the observed photon flux is given by

$$N(E) = \int_{T_{\text{out}}}^{T_{\text{in}}} \left(\frac{T}{T_{\text{in}}} \right)^m B(E, T) \frac{dT}{T_{\text{in}}}, \quad (7)$$

where the temperature of the outer edge of the disk can be regarded as $T_{\text{out}} = 0$. So the diskbb model is effectively the

Figure 5. Comparison between the Band function fitting and the mBB model fitting for the time-integrated spectrum between 20 and 30 s. The spectra have been rebinned into wider bins for clarity. Top panels: observed count spectrum vs. model. Top left panel shows the Band function fitting, and top right panel shows the mBB model fitting. Bottom panels: the deconvolved photon spectrum plots. Bottom left panel shows the Band function fitting, the red line is the theoretical photon spectrum of the Band function, and the data points are the “observed” photon flux that is obtained by deconvolving the observed count spectrum using instrument responses. Bottom right panel: same as the bottom left panel, but for the mBB model fitting where the red line is the theoretical photon spectrum of the multicolor blackbody (mBB) model.

same as the model of Ryde et al. (2010), in which the temperature distribution is normalized by $T_{\max}$ (T_{in} in the diskbb model).

It is worth pointing out that our model is slightly different from Ryde et al. (2010). In Ryde et al. (2010), they assumed a probability distribution of the temperature. In our model, the

distribution of the photosphere emission luminosity as a function of temperature is more directly related to the physics of the GRB fireball, and the power-law index m of the distribution normalized by $T_{\min}$ decides the shape of the low- and middle-energy parts of the spectrum. If $T_{\min}$ is small enough to be outside the low-energy limit of the instrument, the observed spectrum becomes

Figure 6. Parameter constraints of the mBB model (left) and Band function model (right) for time-integrated spectrum between 20 and 30 s. Histograms and contours show the likelihood map of the parameter-constraint outputs by our *McSpecFit* package. Red crosses mark the best-fit values and 1σ error bars.

Table 2

The Comparison of the BIC for the Time-resolved Spectral Fitting of GRB 081221 with the BB, the mBB, and the 2BBPL Models

Time	BIC _{BB}	BIC _{mBB}	BIC _{2BBPL}	BIC _{mBB} – BIC _{BB}	BIC _{2BBPL} – BIC _{BB}
0.00–0.67	256.05	265.93	276.29	9.88	20.24
0.67–0.77	163.06	174.96	186.09	11.90	23.03
0.77–0.87	146.14	158.49	169.80	12.35	23.66
0.87–0.97	132.97	144.91	156.45	11.94	23.48
0.97–1.07	154.86	166.57	178.07	11.71	23.21

(This table is available in its entirety in machine-readable form.)

Table 3

The Fitting Results of the Time-integrated Spectrum of GRB 081221 from 20 to 30 s Using the mBB and Band Function Models

$kT_{\min}$ (keV)	$kT_{\max}$ (keV)	m	PGSTAT/dof	BIC
mBB Model				
4.4 ± 0.3	$57.0^{+1.6}_{-1.4}$	$-0.46^{+0.05}_{-0.06}$	484.2/362	507.8
Band function model				
α	β	E_p	PGSTAT/dof	BIC
-0.60 ± 0.03	$-3.3^{+0.1}_{-0.2}$	$90.1^{+1.6}_{-1.2}$	468.1/362	491.7

the Band or Comptonized cutoff power-law spectrum. Otherwise, if $T_{\min}$ is high enough to be comparable to the $T_{\max}$, the observed spectrum is close to a pure blackbody.

In this paper, we systematically analyze the time-integrated and time-resolved spectra of the prompt emission of GRB 081221 based on the *Fermi*/GBM data. We find that the

time-integrated spectrum is well fitted by the mBB model and the time-resolved spectra can be well fitted by the BB model (without any nonthermal power-law component), implying that the prompt emission of GRB 081221 may be dominated by the photospheric emission. Our results are summarized as follows:

1. The time-integrated spectrum during the bright phase (from 20 to 30 s since the trigger) of GRB 081221 observed with *Fermi*/GBM has a broad plateau in the 15–180 keV band and is well fitted by the mBB model, yielding $kT_{\min} = 4.4 \pm 0.3$ keV, $kT_{\max} = 57.0^{+1.6}_{-1.4}$ keV, $m = -0.46^{+0.05}_{-0.06}$.
2. As for the time-resolved spectra, although the BB model is not the best-fit model when the whole burst is divided into 40 slices, we obtain acceptable fits with the single-blackbody model (without the power-law component), which is simpler compared to the 2BB plus PL model of Basak & Rao (2013). The kT of the main burst increases rapidly from ~ 9 to ~ 20 keV. When the burst is divided into 250 slices, the BB model is much more preferred than the Band model and the 2BB plus PL model, based on the BIC. This means that the evolution of the spectrum has a great influence on the time-integrated spectrum, and hence the time binning greatly affects the theoretical interpretation of the observed time-integrated and even time-resolved spectra.

Our results indicate that the mBB should be the main intrinsic spectral component of GRB 081221, which is a superposition of a series of blackbodies with different temperatures arising at different times of the prompt phase. The identification of the photosphere origin of GRB 081221 suggests that the jet composition of this burst is a matter-dominated fireball. On the other hand, the spectra of some bursts such as GRB 130606B (Zhang et al. 2016) are adequately modeled by the fast cooling synchrotron radiation model (Uhm & Zhang 2014), with no evidence of a thermal photosphere emission component, which suggests a Poynting-flux-dominated jet composition. The coexistence of both types of GRBs suggests that GRB jet composition is likely diverse, with different bursts having different degrees of magnetization from the central engine (e.g., Gao & Zhang 2015).

We are very grateful to the referee for giving valuable comments and suggestions. We acknowledge the use of the public data from the *Fermi* data archives. This work was supported by the National Basic Research Program (973 Program) of China (grants 2014CB845800), the National Natural Science Foundation of China (grant Nos. 11275314, 11673068, 11473022, 11503011, 11275057, 11543004, 11233006, 11822304, and 11603006), the Open Research Program of Key Laboratory for the Structure and Evolution of Celestial Objects (OP201403 and OP201703), key scientific and technological project of Henan province (No. 172102310334), the Key Research Program of Frontier Sciences (QYZDB-SSW-SYS005), and the Strategic Priority Research Program “multi-waveband gravitational wave Universe” (grant No. XDB23000000) of the Chinese Academy of Sciences, the Fundamental Research Funds for the Central Universities, Nanyang Normal University Doctoral Fund (15064), and the Key Scientific Research Project in Universities of Henan Province (grant 15A160001). B.-B.Z. acknowledges the support from the National Thousand Young Talents program of China. Part of this work used B.-B.Z.’s personal IDL code library ZBBIDL and personal Python library ZBBPY. The computation resources used in this work are owned by Scientist Support LLC.

ORCID iDs

Bin-Bin Zhang <https://orcid.org/0000-0003-4111-5958>
 Xue-Feng Wu <https://orcid.org/0000-0002-6299-1263>
 En-Wei Liang <https://orcid.org/0000-0002-7044-733X>
 Tong Liu <https://orcid.org/0000-0001-8678-6291>
 Yun-Feng Liang <https://orcid.org/0000-0002-6316-1616>
 Lin Lin <https://orcid.org/0000-0003-1138-8146>
 Bing Zhang <https://orcid.org/0000-0002-9725-2524>

References

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, *ApJL*, **706**, L138
 Abramowicz, M. A., Novikov, I. D., & Paczynski, B. 1991, *ApJ*, **369**, 175
 Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, *ApJ*, **697**, 1071
 Axelsson, M., Baldini, L., Barbiellini, G., et al. 2012, *ApJL*, **757**, L31
 Axelsson, M., & Borgonovo, L. 2015, *MNRAS*, **447**, 3150
 Band, D., Matteson, J., Ford, L., et al. 1993, *ApJ*, **413**, 281
 Basak, R., & Rao, A. R. 2013, *ApJ*, **768**, 187
 Bégué, D., & Pe’er, A. 2015, *ApJ*, **802**, 134
 Beloborodov, A. M. 2011, *ApJ*, **737**, 68
 Borgonovo, L., & Ryde, F. 2001, *ApJ*, **548**, 770
 Chandra, P., & Frail, D. A. 2008, *GCN*, **8748**, 1
 Cummings, J. R., Barthelmy, S. D., Baumgartner, W. H., et al. 2008, *GCN*, **8708**, 1
 Deng, W., & Zhang, B. 2014, *ApJ*, **785**, 112
 Fan, Y.-Z., Wei, D.-M., Zhang, F.-W., & Zhang, B.-B. 2012, *ApJL*, **755**, L6
 Gao, H., & Zhang, B. 2015, *ApJ*, **801**, 103
 Ghirlanda, G., Pescalli, A., & Ghisellini, G. 2013, *MNRAS*, **432**, 3237
 Goldstein, A., Burgess, J. M., Preece, R. D., et al. 2012, *ApJS*, **199**, 19
 Golenetskii, S., Aptekar, R., Mazets, E., et al. 2008, *GCN*, **8694**, 1
 Golenetskii, S. V., Mazets, E. P., Aptekar, R. L., & Ilinskii, V. N. 1983, *Natur*, **306**, 451
 Goodman, J. 1986, *ApJL*, **308**, L47
 Gruber, D., Goldstein, A., Weller von Ahlefeld, V., et al. 2014, *ApJS*, **211**, 12
 Guiriec, S., Connaughton, V., Briggs, M. S., et al. 2011, *ApJL*, **727**, L33
 Guiriec, S., Daigne, F., Hascoët, R., et al. 2013, *ApJ*, **770**, 32
 Hoversten, E. A., Baumgartner, W. H., Burrows, D. N., et al. 2008, *GCN*, **8687**, 1
 Ito, H., Nagataki, S., Ono, M., et al. 2013, *ApJ*, **777**, 62
 Kaneko, Y., Preece, R. D., Briggs, M. S., et al. 2006, *ApJS*, **166**, 298
 Kargatis, V. E., Liang, E. P., Hurley, K. C., et al. 1994, *ApJ*, **422**, 260
 Kuin, N. P. M., & Hoversten, E. A. 2008, *GCN*, **8703**, 1
 Larsson, J., Racusin, J. L., & Burgess, J. M. 2015, *ApJL*, **800**, L34
 Larsson, J., Ryde, F., Lundman, C., et al. 2011, *MNRAS*, **414**, 2642
 Lu, R.-J., Hou, S.-J., & Liang, E.-W. 2010, *ApJ*, **720**, 1146
 Lundman, C., Pe’er, A., & Ryde, F. 2013, *MNRAS*, **428**, 2430
 Meegan, C., Lichti, G., Bhat, P. N., et al. 2009, *ApJ*, **702**, 791
 Meng, Y.-Z., Geng, J.-J., Zhang, B.-B., et al. 2018, *ApJ*, **860**, 72
 Mészáros, P., & Rees, M. J. 2000, *ApJ*, **530**, 292
 Mizuta, A., Nagataki, S., & Aoi, J. 2011, *ApJ*, **732**, 26
 Pe’er, A. 2008, *ApJ*, **682**, 463
 Pe’er, A., Barlow, H., O’Mahony, S., et al. 2015, *ApJ*, **813**, 127
 Pe’er, A., & Ryde, F. 2011, *ApJ*, **732**, 49
 Peng, F.-K., Liang, E.-W., Wang, X.-Y., et al. 2014, *ApJ*, **795**, 155
 Preece, R. D., Briggs, M. S., Mallozzi, R. S., et al. 1998, *ApJL*, **506**, L23
 Rees, M. J., & Mészáros, P. 2005, *ApJ*, **628**, 847
 Ryde, F. 2005, *ApJL*, **625**, L95
 Ryde, F., Axelsson, M., Zhang, B. B., et al. 2010, *ApJL*, **709**, L172
 Ryde, F., & Pe’er, A. 2009, *ApJ*, **702**, 1211
 Salvaterra, R., Campana, S., Vergani, S. D., et al. 2012, *ApJ*, **749**, 68
 Schwarz, G. 1978, *AnSta*, **6**, 461
 Strohm, M. C., & Hoversten, E. A. 2008, *GCN*, **8701**, 1
 Toma, K., Wu, X.-F., & Mészáros, P. 2011, *MNRAS*, **415**, 1663
 Uhm, Z. L., & Zhang, B. 2014, *NatPh*, **10**, 351
 Wei, J.-J., Wu, X.-F., & Melia, F. 2016, *MNRAS*, **463**, 1144
 Wilson-Hodge, C. A. 2008, *GCN*, **8704**, 1
 Yu, H.-F., van Eerten, H. J., Greiner, J., et al. 2015, *A&A*, **583**, A129
 Zhang, B. 2011, *CRPhy*, **12**, 206
 Zhang, B.-B., Uhm, Z. L., Connaughton, V., et al. 2016, *ApJ*, **816**, 72
 Zhang, B.-B., Zhang, B., Castro-Tirado, A. J., et al. 2018, *NatAs*, **2**, 69
 Zhang, B.-B., Zhang, B., Liang, E.-W., et al. 2011, *ApJ*, **730**, 141