On the Spectral Peak Energy of Swift Gamma-Ray Bursts

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Abstract

Owing to the narrow energy band of the Swift Burst Alert Telescope (BAT), several urgent issues remain unsolved. We systematically study the properties of a refined sample of 283 Swift/BAT gamma-ray bursts (GRBs) with well-measured spectral peak energy ($E_p$) at a high confidence level greater than $3\sigma$. We find that the duration ($T_{90}$) distribution of Swift bursts still exhibits an evident bimodality with a more reliable boundary of $T_{90} \approx 1.06$ s instead of 2 s as found for previously contaminated samples, including bursts without well-peaked spectra, which is very close to the $\sim 1.27$ and $\sim 0.8$ s values suggested in the literature for the Fermi/Gamma-ray Burst Monitor and Swift/BAT catalogs, respectively. The Swift/BAT short and long bursts have comparable mean $E_p$ values of $87^{+112}_{-73}$ and $85^{+46}_{-40}$ keV, similar to what was found for both types of BATSE bursts, which indicates that the traditional short–hard/long–soft scheme may not be tenable for certain detector energy windows. We also statistically investigate the consistency of distinct methods for $E_p$ estimates and find that a Bayesian approach and BAND function (Band et al.) can always provide consistent evaluations. In contrast, the frequently used cutoff power-law model matches two other methods for lower $E_p$ and overestimates the $E_p$ by more than $70\%$, as $E_p > 100$ keV. Peak energies of X-ray flashes, X-ray-rich bursts, and classical GRBs could be an evolutionary consequence of moving from thermal-dominated to nonthermal-dominated radiation mechanisms. Finally, we find that the $E_p$ and the observed fluence ($S$) in the observer frame are correlated as $E_p \approx [S/(10^{-3} \text{ erg cm}^{-2})]^{0.28} \times 117.5^{+44.7}_{-32.4}$ keV, which might be a useful indicator of GRB peak energies.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); High energy astrophysics (739); Astronomy data analysis (1858); Astrostatistics distributions (1884); Interstellar synchrotron emission (856); Interstellar thermal emission (857); Extragalactic astronomy (506)

1. Introduction

Gamma-ray bursts (GRBs) are the strongest and brightest explosions in the universe and were first seen in 1967 by the Vela satellite. That discovery has led researchers to pursue the nature of its formation, structure, and evolution (e.g., Piran 2004; Zhang & Mészáros 2004; Mészáros 2006; Nakar 2007; Berger 2014) since the first GRB phenomenon was reported by Klebesadel et al. (1973). The duration parameter ($T_{90}$) of prompt $\gamma$-rays is defined as the time over which a burst emits the middle 90% of its total measured photon counts by satellites. In terms of $T_{90}$, it is found that GRBs can be divided into long–soft and short–hard classes whose boundary is around 2 s. The bimodal category of $T_{90}$ is supported by Burst and Transient Source Experiment (BATSE: 20 keV–10 MeV), Swift Burst Alert Telescope (BAT: 15–150 KeV) and Fermi GRB Monitor (GBM: 8 keV–40 MeV) data (e.g., Kouveliotou et al. 1993; Zhang & Choi 2008; Zitouni et al. 2015, 2018; Zhang et al. 2016; Tarnopolski 2017), although the BAT detector prefers softer $\gamma$-rays than the other two monitors. However, some authors insisted there are three (Chattopadhayay et al. 2007; Horváth & Tóth 2016) or even five (Chattopadhayay & Maitra 2017; Tóth et al. 2019) GRB subgroups. Very recent investigations of the skewed distributions in the plane of hardness ratio versus $T_{90}$ confirm these additional components to likely be artificial (Tarnopolski 2019a, 2019b). Therefore, the classification of GRBs according to $T_{90}$ is still controversial and urgent, particularly in view of spectral properties (Zhang et al. 2009). In this context, determining out how $T_{90}$ is distributed using a good spectrum measurement is an important issue.

An important parameter of the $nF_n$ spectrum of the prompt $\gamma$-rays is the peak energy $E_p$, which presents the general spectral properties of GRBs. Previously, authors studied its statistical distributions and found the typical $E_p$ is distributed over a broad energy range from a few keV to MeV (e.g., Preece et al. 2000; Sakamoto et al. 2004). Usually, bright GRBs have larger energy outputs peaking around hundreds of keV to sub-MeV (Preece et al. 2016), which is similar to the $E_p$ distribution of short faint GRBs detected by Konus-Wind (Svinkin et al. 2016). Some less luminous GRBs are labeled X-ray-rich GRBs (XRBs), with $E_p < 100$ keV typically. There are softer $\gamma$-ray events called X-ray flashes (XRFs) with spectra peaking below $\sim 30$ keV (Barraud et al. 2005; Sakamoto et al. 2005). Katsukura et al. (2020) showed that XRBs and XRFs are not isolated populations from bright GRBs but a phenomenal extension on the basis of Swift’s multiwavelength observations. The photosphere model is usually applied to interpret $E_p$ depending on the photon temperature of a fireball as it cools adiabatically (Ryde 2004; Beloborodov 2013), while the dissipative photosphere model predicts that $E_p$ results from the electron temperature (Giannios 2012). Other important possible mechanisms of $E_p$ formation are internal shock (e.g., Bosnjak & Daigne 2014; Yü et al. 2015) and internal-collision-induced magnetic reconnection and turbulence (Zhang & Yan 2011). The latter is controlled by the synchrotron radiation of relativistic electrons with an energy distribution of $N(e) \propto e^{-p}$, in which $p$ is the power-law index and $\gamma_{\text{min}}(>\gamma_{\text{min}})$ denotes the electronic Lorentz factor. Regarding the radiation processes generating lower $E_p$ of XRFs, several theories, such as the high-redshift GRB model, the off-axis jet model, and the sideways expanding opening-angle model, are summarized in Katsukura et al. (2020).

On the other hand, the observed $E_p$ distribution is easily biased by the energy window of different $\gamma$-ray detectors if
only the energy coverage is not wide enough. For example, Zhang et al. (2018) studied the $E_p$ distributions and energy correlations of $E_p$ versus peak luminosity ($L_p$), $E_p$ versus isotropic energy ($E_{iso}$), and $E_p$ versus jet-corrected energy ($E_{\gamma}$) for large samples including 31 short and 252 long GRBs with a measured $E_p$, of which 160 and 105 bursts are taken from BAT and GBM catalogs between 2004 December and 2017 November, respectively. They found the mean values to be $\pm 98$ keV for long and short GRBs, correspondingly, which is in agreement with the $E_p$ distribution of 80 Swift long GRBs gained by Katsukura et al. (2020) recently. Due to the broader energy bands of BATSE and GBM, extensive multiwavelength observations by the two satellites give similar $E_p$ distributions, with a mean value of $\sim 200$ keV (Preece et al. 2000, 2016; Goldstein et al. 2013; Gruber et al. 2014). In contrast, the peak energies of BATSE/GBM GRBs are on average two times larger than those of Swift/BAT bursts owing to the diverse energy bands of the detectors. This leads to a significant fraction of XRFs and XRBs having with lower $E_p$ being easily triggered by Swift (Butler et al. 2007; Katsukura et al. 2020). As shown in Figure 1, Swift/BAT’s narrower energy window can only detect lower $E_p$, as in case I, if the $E_p$ of a burst is located outside of the BAT energy range of, as displayed for case II, how can we know where the GRB spectrum would peak? Of course, if only case II occurs in a wider energy window of detectors like Fermi/GBM, as illustrated in Figure 1, $E_p$ can be jointly measured with the aid of other satellites (Zhang et al. 2018; Katsukura et al. 2020). Additionally, one may apply the statistically Bayesian method (Butler et al. 2007) or the empirically Comptonized model (e.g., Sakamoto et al. 2008; Lien et al. 2016) to infer the $E_p$ in both cases I and II. However, whether these inferred peak energies are consistent with each other or not is a fundamental and crucial problem. Furthermore, the diversity of $E_p$ among the different energy channels also motivates us to explore the possible emission mechanisms for its physical origins.

In Section 2 we present the data preparation and methodology used in the measurement of $E_p$. In Section 3 we show the $T_{90}$ distribution of GRBs with well-constrained $E_p$. Some results related to the empirical $E_p$ are provided in Section 4 to show the underlying import of the $E_p$ observations on the dominant radiation mechanisms as illustrated in Section 5. Conclusions and discussions are given in Section 6.

2. Methods and Data

There are three empirical methods that are popularly used to estimate the $E_p$. In general, most fluence-averaged spectra of GRBs can be successfully fitted by the following BAND function (Band et al. 1993):

$$N_{E,BAND}(E) = A_o \begin{cases} \left( \frac{E}{100 \text{ keV}} \right)^\alpha \exp \left[ -\left( \frac{E}{E_{p,o}} \right)^{\alpha + 2} \right] & \text{for } E < E_{\text{break}}, \\ \left( \frac{E}{100 \text{ keV}} \right)^\beta \exp \left( \beta - \alpha \right) \left( \frac{E_{\text{break}}}{100 \text{ keV}} \right)^{\alpha - \beta} & \text{for } E \geq E_{\text{break}}, \end{cases}$$

where $A_o$ is the normalization factor at 100 keV in units of photons $s^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$, and $\alpha$ and $\beta$ are respectively low and high power-law indices in photon number. Throughout the paper, the $E_{p,o}$ given by the BAND function fit is called the

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Figure 1. Sketch of two representative types of GRB spectra located in the Swift/BAT (dark gray) and Fermi/GBM (light gray) energy windows.
observed peak energy in the $E^2N_E$ or $\nu F_\nu$ spectrum and $E_{\text{break}} = E_{p,o}(\alpha - \beta)/(\alpha + 2)$ denotes the break energy in the region where two power-law segments connect. To guarantee that the peak energy is yielded, $\alpha > -2$ and $\beta < -2$ are typically required. Equation (1) is valid for cases I and II only when the GRB spectrum peaks within the energy window of a detector. Observationally, only about one-third of Swift GRBs within the BAT window can be directly fitted with this method.

The treatment in case II for Swift bursts is to combine the data with other instruments with a broader energy region in order to infer the expected $E_{p,o}$ jointly.

The second way of estimating $E_p$ is to use the cutoff power-law (CPL) or Comptonized model (Sakamoto et al. 2008), which makes Equation (1) degenerate into the subset form in the limit of $\beta \to \infty$ as

$$N_E = A_c \left(\frac{E}{100\text{ keV}}\right)^{\alpha_{\text{CPL}} + 2} \exp\left[-\frac{(\alpha_{\text{CPL}} + 2)E}{E_{p,c}}\right],$$

in which $A_c$ is the normalization factor at 100 keV in units of photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$, $\alpha_{\text{CPL}}$ and $E_{p,c}$ are spectral index and peak energy, respectively. The third method is the popular and unbiased Bayesian approach (Butler et al. 2007) employed to estimate the peak energy $E_{p,b}$ in the posterior distribution of probability as

$$P(\ln E_{p,b}) \propto \exp\left[-0.5 \ln \left(\frac{E_{p,b}}{300\text{ keV}}\right)\right]^2/\sigma_{E_{p,b}}^2,$$

where the zero probability has been assumed for $E_{p,b} > 10^4$ keV and $E_{p,b} < 1$ keV. At the same time, two parameters, $\alpha = -1.1$ and $\beta = -2.3$, taken from the BATSE data catalog, in Equation (1) have been set for two prior exponential probability distributions (Butler et al. 2007). Note that the CPL and the Bayesian approaches were initially proposed to estimate peak energies for case II are available for case I as well. We emphasize that Equations (2) and (3) are two separate ways to infer the $E_p$ no matter where the GRB spectra peak.

For the purpose of understanding physical properties of prompt $\gamma$ emissions, the observed GRB spectra are usually “fitted” to any one of the chosen models in Equations (1)–(3). Table 1 compares these empirical peak energies. To investigate the consistency of different $E_p$ determinations, we select Swift/BAT bursts with well-constrained $E_p$ detected from 2004 December and 2018 October. Our sample selection criteria are defined as follows: (1) use Swift/BAT GRBs only; (2) select GRB spectra fitted with the BAND function successfully, regardless of $E_p$ being inside or outside the energy window of Swift/BAT; and (3) choose GRBs with measured $E_{p,o}$ at a higher confidence level of signal-to-noise ratio ($S/N$) $> 3$. Thus, out of 1256 Swift/BAT bursts, 283 (15 short and 268 long GRBs with both $E_{p,o}$ and $E_{p,b}$ match the above standards and are directly taken from Nat Butler’s Swift BAT+XRT (+optical) repository. In total, 266 (15 short and 251 long GRBs with known $E_{p,o}$) are obtained from the Swift/BAT GRB Catalog. In addition, we also collect the $T_{90}$ values for 279 GRBs from the official Swift GRB table3 and 4 GRBs (900621A, 100514A, 130306A, and 130807A) from the Gamma-ray Coordinates Network,6 and the redshifts of 92 GRBs from JG’s homepage.7 Note that in our sample there are 37 GRBs with $E_{p,o} > 150$ keV that are already beyond the Swift/BAT energy window.

### 3. Durations and Classifications

In this section, we display the temporal and spectral results of both short and long GRBs with well-confirmed $T_{90}$ and $E_p$ simultaneously. In the past 12 years several authors have studied the $T_{90}$ distribution of Swift GRBs and found that bimodal rather than triple GRB groups are preferred (e.g., Zhang & Choi 2008; Zitouni et al. 2015, 2018; Zhang et al. 2016). Figure 2 shows the $T_{90}$ distribution of 283 Swift bursts with confident $E_{p,o}$ at the $\gtrsim 3\sigma$ level. The two-Gaussian fit to the data demonstrates that the duration distribution peaks at $0.21^{+0.31}_{-0.12}$ s, with a spread of 0.93 dex for short bursts and at $42.66^{+2.00}_{-1.92}$ s with a spread of 1.11 dex for long GRBs. The best fit returns a good reduced chi-squared value of $\chi^2_\nu \simeq 1.19$, indicating two classes are evidently reconfirmed and separated at $T_{90} \approx 1.06$ s, other than the 2 s value shown by CGRO/BATSE data in Kouveliotou et al. (1993) or Swift/BAT normal observations by Zhang & Choi (2008) and Zhang et al. (2016). However, the new dividing line at $T_{90} = 1.06$ s is very close to the 1.27 s value of GBM long bursts, which is systematically longer than those of GBM/SGRBs missions, which is deeply affected by the threshold effect (Zhang et al. 2016). Additionally, the durations of Swift/BAT long bursts have a relatively wider distribution and are systematically longer than those of GBM/BATSE long GRBs. We attribute this to the fact that BAT is more sensitive to lower-soft GRBs (Gehrels et al. 2004), especially short GRBs with

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5. http://butler.lab.asu.edu/Swift/index.html
6. https://swift.gsfc.nasa.gov/results/hatfgbrcat/
7. https://swift.gsfc.nasa.gov/archive/
8. https://swift.gsfc.nasa.gov/
9. http://www.mpch.mpg.de/~jcg/grbgen.html
extended emission (EE) that would easily confuse the classification in terms of $T_{90}$ (Zhang et al. 2016).

4. Properties of Empirical Peak Energies

Here, the consistency of the above different inferences of peak energy is checked statistically. Taking into account the $E_p$ diversity, we subsequently re-examine the peak energy versus the fluence in the observer frame.

4.1. Comparing Peak Energies between Different Models

We now move to investigate the similarities and differences in peak energies given by the different methods illustrated in Section 2. Figure 3 is plotted for the cumulative fraction distributions of all selected GRBs in the upper panel and their histograms in the lower panel for three kinds of $E_p$ in both the observer and the rest frames, from which we are able to see the obvious difference between the intrinsic $E_{p,i} = (1 + z)E_{p,o}$ and the observed $E_{p,o}$ distributions. In fact, a Kolmorogov–Smirnov (K-S) test of the $E_{p,o}$ and $E_{p,i}$ distributions gives $D = 0.66$ with a $p$-value of $9.48 \times 10^{-25}$, showing that they are not drawn from the same parent distribution, of which the median of the $E_{p,i}$ is about three times larger than that of the $E_{p,o}$. Although $E_{p,o}$, $E_{p,b}$, and $E_{p,c}$ seem to be identically distributed, an Anderson–Darling (A–D) test demonstrates in the first set of Table 2 that $E_{p,o}$ and $E_{p,c}$ are differentially distributed, while the other two pairs of peak energies share the same distributions. The observer-frame mean values of peak energies are correspondingly $E_{p,o} \approx 85.1^{+62.8}_{-36.1}$ keV, $E_{p,b} \approx 79.4^{+38.6}_{-39.4}$ keV, and $E_{p,c} \approx 99.9^{+108.9}_{-52.2}$ keV, all of which are lower than the rest-frame peak energy of $E_{p,i} \approx 245.5^{+44.3}_{-122.3}$ keV and the scatter of the $E_{p,c}$ measurement is comparably larger than that of either $E_{p,o}$ or $E_{p,b}$ in the observer frame. Note that we have used Fermi/GBM data to constrain the $E_{p,o}$ of a small fraction (~13%) of Swift bursts, as their peak energies exceed the BAT upper limit of 150 keV.

$E_{p,o}$ generally evolves with time because of spectral evolution (e.g., Zhang et al. 2012). In particular, most long GRBs with higher redshift exhibit a trend of hard–soft spectral evolution (Norris et al. 2000; Daigne & Mochkovitch 2003), while short GRBs with lower redshift show no significant spectral evolutions (Norris & Bonnell 2006; Zhang et al. 2006). However, it is not clear whether there is a dependence of the $E_p$ estimates on redshift for both short and long bursts. We compare the three observer-frame $E_p$ in Figure 4 where the peak energies of short bursts have a distribution superficially different from those of long bursts. Surprisingly, the second set of Table 2 from the A–D tests demonstrates that the estimates of $E_{p,o}$, $E_{p,b}$, and $E_{p,c}$ are consistent with each other for short GRBs, and similar to long bursts whose $E_p$ distributions are statistically the same except for the inconformity between $E_{p,o}$ and $E_{p,c}$. One can logically infer that the distributional difference of $E_{p,o}$ from $E_{p,c}$ in the complete $E_p$ sample is slightly caused by long GRBs and the $E_p$ estimates based on different models are not connected with redshifts or durations evidently. Interestingly, our highly confident peak energy samples return the consistent mean values of $E_{p,o}$ to be $\sim 87^{+119}_{-49}$ keV and $\sim 85^{+101}_{-46}$ keV for short and long GRBs, respectively, which greatly deviates from our traditional comprehension of short–hard versus long–soft bursts. The possible reason is that most Swift short GRBs are accompanied by EE components that soften GRB energy spectra, and Swift’s instrumental design.
Figure 3. Comparisons between three lab-frame peak energies inferred from diverse methods along with the $E_{p,i}$ in the rest frame. The two vertical dashed lines represent the energy ranges of Swift/BAT in logarithmic scale.

Table 2
Parameters of the A–D Test between Different $E_p$ Distributions for a Significance Level of $\alpha = 0.01$

| GRB Type | $E_p$ Pair | Sample Size | AD-stat | $p$-value | AD-crit | Null Hypothesis |
|----------|------------|-------------|---------|-----------|---------|-----------------|
| Complete | $E_{p,b}/E_{p,o}$ | 283:283 | 1.614   | 0.151     | 3.8705  | accepted        |
| Complete | $E_{p,o}/E_{p,c}$ | 283:266 | 5.477   | 0.002     | 3.8702  | rejected        |
| Complete | $E_{p,b}/E_{p,c}$ | 283:266 | 2.655   | 0.041     | 3.8702  | accepted        |
| Short    | $E_{p,b}/E_{p,o}$ | 15:15    | 1.264   | 0.239     | 3.7296  | accepted        |
| Short    | $E_{p,o}/E_{p,c}$ | 15:15    | 0.384   | 0.896     | 3.7296  | accepted        |
| Short    | $E_{p,b}/E_{p,c}$ | 15:15    | 0.596   | 0.673     | 3.7296  | accepted        |
| Long     | $E_{p,b}/E_{p,o}$ | 268:268  | 1.290   | 0.235     | 3.8700  | accepted        |
| Long     | $E_{p,o}/E_{p,c}$ | 268:251  | 5.416   | 0.002     | 3.8697  | rejected        |
| Long     | $E_{p,b}/E_{p,c}$ | 268:251  | 3.192   | 0.022     | 3.8697  | accepted        |
| LE       | $E_{p,b}/E_{p,o}$ | 55:55    | 5.279   | 0.002     | 3.8377  | rejected        |
| LE       | $E_{p,o}/E_{p,c}$ | 55:53    | 8.454   | 5.7E-5    | 3.8370  | rejected        |
| LE       | $E_{p,b}/E_{p,c}$ | 55:53    | 0.913   | 0.407     | 3.8370  | rejected        |
| ME       | $E_{p,b}/E_{p,o}$ | 191:191  | 1.769   | 0.123     | 3.8667  | accepted        |
| ME       | $E_{p,o}/E_{p,c}$ | 191:185  | 8.284   | 7.7E-5    | 3.8665  | rejected        |
| ME       | $E_{p,b}/E_{p,c}$ | 191:185  | 3.902   | 9.6E-3    | 3.8665  | rejected        |
| HE       | $E_{p,b}/E_{p,o}$ | 37:37    | 0.599   | 0.656     | 3.8181  | accepted        |
| HE       | $E_{p,o}/E_{p,c}$ | 37:28    | 10.727  | 7.6E-7    | 3.8097  | rejected        |
| HE       | $E_{p,b}/E_{p,c}$ | 37:28    | 9.808   | 6.5E-6    | 3.8097  | rejected        |
makes them easier to detect. Notably, Ghirlanda et al. (2004) also found the averaged $E_p$ values of short and long bursts to be statistically the same, even for the BATSE detector, which has broader energy coverage. Hence, one can conclude that $E_p$ is not an optimized parameter, indicating the hardness of GRB spectra, as the two classes of GRBs could be essentially identical from the perspective of the radiation mechanism. More interestingly, this is very similar to previous conclusions based on the relation of hardness ratio (HR) with $T_{90}$ for Swift/BAT short and long GRBs with fluences better fitted by a spectral model (Sakamoto et al. 2011; Lien et al. 2016; Zhang et al. 2016).

Furthermore, we study the distributional consistency of three kinds of $E_p$ in Figure 5, from which the burst numbers in each energy channel are respectively 55 for the low-energy (LE) band below 50 keV, 191 for the middle-energy (ME) band between 50 and 150 keV, and 37 for the high-energy (HE) band above 150 keV. Notably, the diverse energy bands roughly correspond to the energy scopes of XRFs, XRBs, and classical GRBs (C-GRBs) defined by Katsukura et al. (2020). The A–D tests have also been done and returned the results in the third set of Table 2, in which we find that $E_{p,b}$ and $E_{p,c}$ share with the same distribution (AD $= 0.91$ and $p = 0.41$) in the LE wavelength, while $E_{p,b}$ and $E_{p,o}$ are identically distributed in both ME and HE wavelengths due to smaller AD statistics and larger $p$-values. Moreover, if considering Figures 3–5 as a whole, we note that the Bayesian approach in Equation (3) can always return very similar $E_{p,b}$ to those $E_{p,o}$ fitted by the BAND function in Equation (1). On the contrary, the $E_{p,c}$ estimated by the CPL model of Equation (2) cannot ideally match the observed peak energies given by Equation (1) for all classes of GRBs but the short ones. It needs to be emphasized that $E_{p,o}$, compared with either $E_{p,b}$ or $E_{p,o}$, will be over-estimated when the peak energies are larger than $\sim$100 keV.

4.2. Peak Energy versus Fluence

Using the complete BATSE 5B Spectral Catalog, Goldstein et al. (2010) found that roughly 65% of the bolometric fluence ($S_{\text{bolo}}$) distribution for short GRBs overlaps with that for long GRBs with the peak position being an order of magnitude larger than the fluence distribution of short GRBs. Here, the ratio of the observed fluence ($S_\gamma$) overlap of short to long GRBs in our Swift/BAT GRB sample is approximately 80% and their discrepancy is similar. Very recently, Katsukura et al. (2020) studied the spectral properties of 80 Swift long bursts (26 XRFs, 41 XRBs, and 13 C-GRBs) with well-constrained $\gamma$-ray and X-ray spectral parameters and found that three subclasses can be clearly divided at 30 and 100 keV according to the fluence ratio between channels 1 and 2 of the BAT detector. Simultaneously, they showed a weaker dependence of $E_{p,o}$ on $S_\gamma$ and the XRFs are slightly dimmer than the other two kinds of bursts.

By contrast, our sample including 268 long and 15 short GRBs with well-determined spectra is largely expanded. The $E_{p,o}$–$S_\gamma$ relations in the observer frame for the total 283 Swift GRBs are displayed in Figure 6, which shows that the current relation of $E_{p,o}$ with $S_\gamma$ for Swift long GRBs is tighter than some previous ones (Goldstein et al. 2010; Zhang et al. 2018; Katsukura et al. 2020) and can be well fit by

$$\log E_{p,o} = (3.47 \pm 0.09) + (0.28 \pm 0.02) \times \log S_\gamma, \hspace{1cm} (4)$$

with Spearman correlation coefficient $R = 0.70$ and a chance probability $P = 6.9 \times 10^{-31}$. This implies that the Equation (4) can be employed as an indicator to estimate the $E_p$ of a burst without good spectral breaks. However, the $E_{p,o}$–$S_\gamma$ relation of 15 short GRBs is largely scattered, possibly owing to the limited data points. Note that our $E_{p,o} - S_\gamma$ relation resembles the relation of...
$E_p$ versus photon index $\Gamma$ as $\log E_{p,o} \simeq 3.26 - 0.83\Gamma$, as proposed by Sakamoto et al. (2009) for Swift long GRBs. If combing both of them, one can naturally obtain an expression of $S_{\gamma} \simeq 10^{-(2.96\Gamma+0.76)}$ in units of erg cm$^{-2}$. To analyze the $E_{p,o}$ diversity as well as its possible origins, we draw two boundaries at $E_{p,o} = 30$ and 100 keV in Figure 6 to classify our sample of 283
Swift GRBs into three subgroups, that is 6 XRFs, 176 XRBs, and 101 C-GRBs. By comparing with Katsukura et al. (2020) in the plane of $S_\gamma$ against $E_{p,o}$, we find that our percentages of XRFs, XRBs, and C-GRBs are respectively 2%, 62%, and 36%, which visibly differ from Katsukura et al. (2020), where the vast majority of Swift bursts hold much lower $E_{p,o}$. However, our ratios of different kinds of bursts are very close to those of the raw Swift data.

5. Implications for Radiation Mechanisms

We now focus on the analysis of the potential radiation mechanisms leading to the diverse $E_p$ over a broader energy scope. In physics, the peak energy of GRBs is usually thought to generate from either thermal/quasithermal or nonthermal radiations of relativistic electrons in plasma outflows. In case of the thermal $\gamma$-ray emissions from a dissipative photosphere or blackbody (BB), the observed spectrum can be well described by a Planck function below

$$N_{E, BB}(E) = A_b \left( \frac{E}{1 \text{ keV}} \right)^2 \exp \left( \frac{E}{kT} \right) - 1^{-1}, \quad (5)$$

where $A_b$ is the normalization factor at 1 keV in units of photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$, $k$ is Boltzmann constant, $T$ and $kT$ are respectively absolute temperature in Kelvin and thermal energy in units of keV of the BB. $N_{E, BB}(E)$ reaches its maximum value at a certain peak energy of $E_{p, BB}$.

Following Yu et al. (2015), the synchrotron radiation as the most representative nonthermal mechanism of GRBs can be characterized with the following form:

$$N_{E, syn}(E) = A_s \left( \frac{E}{100 \text{ keV}} \right)^{\alpha'} \text{ for } E < E_{b,1},$$
$$N_{E, syn}(E) = \left( \frac{E}{E_{b,1} \text{ keV}} \right)^{\alpha'} \left( \frac{E}{E_{b,2} \text{ keV}} \right)^{\beta'} \text{ for } E_{b,1} \leq E < E_{b,2},$$
$$N_{E, syn}(E) = \left( \frac{E}{E_{b,1} \text{ keV}} \right)^{\alpha'} \left( \frac{E}{E_{b,2} \text{ keV}} \right)^{\beta'} \text{ for } E \geq E_{b,2},$$

where $A_s$ is the normalization factor at 100 keV in units of photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$, $\alpha'$, $\beta'$, and $\gamma'$ are three spectral power-law indices of the corresponding parts, $E_{b,1}$ and $E_{b,2}$ stand for two break energies in units of keV at some characteristic frequencies, namely the cooling frequency $\nu_c$ and the minimum frequency $\nu_m$ of photons emitted from electrons within a slow-cooling or fast-cooling scenario (Sari et al. 1998). In case of the slow cooling ($\nu_m < \nu_c$), we have $E_{b,1} = h\nu_m$, $E_{b,2} = h\nu_c$, $\alpha' = -2/3$, $\beta' = -(p + 1)/2$, and $\gamma' = -p/2 - 1$. For the fast cooling ($\nu_c < \nu_m$), the critical parameters are set as $E_{b,1} = h\nu_c$, $E_{b,2} = h\nu_m$, $\alpha' = -2/3$, $\beta' = -3/2$, and $\gamma' = -p/2 - 1$. For simplicity, the electronic power-law index of $p = 2.4$ is assumed. No matter which case we choose, the $E^2N_E$ spectra will be expected to peak at a given energy $E_{p, syn}$ ranging from $E_{b,1}$ to $E_{b,2}$ (Yu et al. 2015).

Figure 7 is plotted with Equations (5) and (6) to illustrate the potentially physical forming mechanisms of $E_p$ from the BB and/or the Synchrotron radiations. Here, the average values of

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**Figure 7.** GRB multicolor energy spectra reproduced from BB and synchrotron components. The thick solid and dashed lines represent Synchrotron emissions with $A_s = 1$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$ from the fast and slow electronic cooling, respectively. The thin dashed-dotted and dotted lines denote thermal radiations for the two typical $A_b$ in the text, correspondingly, while the top thick lines show them combined with the synchrotron segment. The two vertical lines show the representative break energies in the synchrotron model.
\[ kT \simeq 10.4^{+4.9}_{-3.7} \text{ keV}, E_{b,1} \simeq 130^{+132}_{-32} \text{ keV to } E_{b,2} \simeq 631^{+581}_{-310} \text{ keV} \]

found by Yu et al. (2015) have been directly utilized to generate the diverse spectra, of which most GRBs have peak energies observed within \( E_{b,1} < E_{p,0} < E_{b,2} \). It is clear that the standard BB spectrum always peaks at \( 3.92 kT \) (\pm 40.77 keV) despite different \( A_b \) factors. Here we take \( A_b = 0.1 \) and 1 photons s \(^{-1} \) cm \(^{-2} \) keV\(^{-1} \) as representative values aligned with the BAT observations. According to the theoretical arguments, \( E_p, \text{BB} \) should have an upper limit or "death" line of 2.82 \( kT \) for a relativistic outflow (Li & Sari 2008; Zhang et al. 2012). Considering the error bars and statistical fluctuations of \( E_{b,1} \) and \( kT \), the predicted \( E_p \) distributions from the BB and the Synchrotron models are to be bridged or overlapped, which is in agreement with the conclusions of Figure 3 drawn by Yu et al. (2015) observationally. At the same time, two 3\( \sigma \) confidence ranges of the predicted peak energies from Equations (5) and (6) are marked with shaded and hatched regions in Figure 6, respectively. Considering the equivalent GRB numbers within different energy ranges, we infer that around 50% of Swift GRBs are better explained by the BB for most XRFs plus XRBs or the synchrotron radiation mechanisms for most C-GRBs, correspondingly (see also Oganesyan et al. 2018, 2019). Instead, only a small fraction of XRBs need to be explained by the combination of thermal and nonthermal components. We naturally concluded that there is an evolutionary consequence of \( E_p \) moving from thermal-dominated to nonthermal-dominated emissions, at least for parts of bursts (see also Beloborodov 2013; Li 2019). Comparing Figures 5 and 6 with Figure 7, one can conclude that GRBs with higher \( E_p > 100 \text{ keV} \) are most likely interpreted by the synchrotron radiations and the CPL model will be invalid for their \( E_p \) estimations.

6. Discussion and Conclusions

Regarding the \( T_{90} \) distribution of Swift/BAT bursts, how many components there are and where they are separated have been topics of interest since the first research by Zhang & Choi (2008). They analyzed the first four-year Swift GRB data and pointed out that two types of GRBs divided at 2 s are preferred. Meanwhile, the intrinsic \( T_{90} \) was also found to be bimodally populated. The classification criteria are confirmed by our recent analysis of Swift/BAT observations with a popular Bayesian information criterion (BIC) method if short GRBs with EE are excluded (Zhang et al. 2016). Note that we did not consider the spectral effects on the \( T_{90} \) determination. Additionally, the \( T_{90} \) distribution are more or less biased by the background level, bin size, threshold, and energy coverage of the detector, sampling standard, and so on. Bromberg et al. (2013) constructed an empirical model using \( T_{90} \) to distinguish the collapsar GRBs from the noncollapsar ones and they proposed classifying Swift short and long bursts at 0.8 \( \pm 0.3 \) s physically. If so, our short GRBs with \( T_{90} < 1 \text{ s} \) probably originated from noncollsars. Since the duration timescale is tightly connected with the radiation region (Zhang et al. 2007), a shorter \( T_{90} \) implies these short GRBs might be produced from even smaller emitting radii, which should put further strict constraints on GRB theories.

Ghirlanda et al. (2004) determined the mean \( E_p \) values of BATSE GRBs to be 355 \( \pm 30 \) keV and 520 \( \pm 90 \) keV for short and long bursts, respectively, values that we can compare to ours. They insisted that it is the low-energy power-law index in the BAND function causing the higher hardness ratio in short against long GRBs. Excitingly, we also find no differences between peak energies of 87\(^{+112}_{-49} \) keV for short bursts and 85\(^{+101}_{-46} \) keV for long ones even within narrower energy bands of Swift/BAT. Consequently, one can conclude that the differences between short and long GRBs are less evident when the sample is restricted to a certain energy window. Moreover, our finding demonstrates that a significant fraction of short GRBs with lower \( E_p \) do exist and could be an important extension to the low end of \( E_p \). Lately, Dereli-Bégéu et al. (2020) sorted Fermi/GBM short and long bursts and reported a correlation of \( T_{90} \times E_p^{0.35} \) that will become less correlative if Swift/BAT short GRBs are included. Note that there is no obvious \( T_{90}-E_p \) relation at all in our \( E_p \)-selected Swift/BAT GRB sample.

Although the \( E_p \) values of Swift/BAT GRBs are on average lower than those of Fermi/GBM or CGRO/BATSE, this surprisingly does not affect the existence and consistency of \( E_p \) in association with luminosity and isotropic energy in the higher \( E_p \) region. In practice, Zhang et al. (2018) found that the power-law relations of \( E_p, t \propto E_p^{0.44} \), \( E_p, t \propto E_p^{0.34} \), and \( E_p, t \propto E_p^{0.20} \) do exist in the Swift/BAT GRB-dominated samples and these empirical correlations are marginally consistent with some previous results. In addition, they noticed for the first time that the power indexes are equal between short and long GRBs for any one of three energy correlations. These accordant results indicate that there is no considerable energetic evolution effect for these energy correlations. Moreover, some recent investigations show that pulse width and photon energy of not only CGRO/BATSE but also Swift/BAT short GRBs are negatively related, with a power-law form similar to that of long bursts, which are also found to be independent of the energy bands of detectors (Li et al. 2020a, 2020b).

To depict the observed GRB spectra, thermal and synchrotron/Comptonized radiation mechanisms are usually favored despite other processes being proposed, especially lower \( E_p \) explanations. This is likely true when the low \( E_p \) cannot be described by a sole BB or a burst does not have a thermal component at all. Lazzati et al. (2005) studied the spectra of 76 BATSE short bursts and found that about 75% of the bursts have spectra inconsistent with a BB-like form. However, previous radiation transfer simulations showed that the Band function could be generated from a thermal origin and the resulting maximum \( E_p \) will rise up to 3 MeV in the source frame (Beloborodov 2013). Note that the high-redshift interpretation (Heise 2013) of lower \( E_p \) may not be trustworthy because the \( E_p \) is not correlated with redshift at least for our sample. Additionally, Katsukura et al. (2020) illustrated that the \( E_p \) diversity cannot be interpreted by the off-axis model and would be caused by some intrinsic mechanisms. Hopefully, the real formation mechanisms of the lower peak energies will be completely revealed theoretically and observationally in the coming era of large telescopes.

Based on the above investigations, we summarize our results as follows. First, we have used a sample of 283 Swift/BAT GRBs with well-measured \( E_p \) to analyze their logarithmic \( T_{90} \) distribution and found that \( T_{90} \) is still bimodally rather than triply distributed. The best fit with a two-Gauss model gives two separated peaks at 0.21 s and 42.66 s divided by a boundary of \( \sim 1.06 \) s, which is consistent with the 1.27 s (Gruber et al. 2014) and 0.8 \( \pm 0.3 \) s values (Bromberg et al. 2013) reported for Fermi/GBM and Swift/BAT catalogs, respectively. Second, we find that the peak energies of Swift/BAT GRBs are comparable with mean peak energies of 87\(^{+112}_{-49} \) keV for short and long bursts, respectively. This is similar to the values found for the BATSE
short and long GRBs by Ghirlanda et al. (2004). Thus, the peak energy may not be a representative parameter describing the spectral hardness. Third, the comparative studies of distinct methods for estimating $E_p$ demonstrate that the Bayesian model and the BAND function can return more consistent $E_p$, while the frequently used cutoff model will evidently overestimate the $E_p$ within a higher energy scope, say $E_p > 100$ keV. Fourth, we theoretically analyze the underlying $E_p$ formation mechanisms under three conditions, thermal, synchrotron radiation, and both (mixed radiations), to explain the $E_{p,\alpha}$ diversity. Approximately half the sample of Swift GRBs, including XRFs and most XRBs, is located in the thermal-dominated regions, while the other half of the sample of Swift GRBs, the majority of them, C-GRBs are contributed by the nonthermal radiation components. Notably, there only a small fraction of XRBs can be interpreted by the mixture of BB and the synchrotron radiation emissions. Finally, we find a tight correlation between $S_e$ and $E_{p,\alpha}$ for the Swift/BAT long GRBs, $E_p \approx [S_e/(10^{-5} \text{ erg cm}^{-2})]^{0.28} \times 117.5^{+44.7}_{-37.4}$ keV, that could serve as indicator of peak energy if only the observed fluence is available.

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