THE TEMPORAL AND SPECTRAL CHARACTERISTICS OF “FAST RISE AND EXPONENTIAL DECAY” GAMMA-RAY BURST PULSES

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ABSTRACT

In this paper, we have analyzed the temporal and spectral behavior of 52 fast rise and exponential decay (FRED) pulses in 48 long-duration gamma-ray bursts (GRBs) observed by the CGRO/BATSE, using a pulse model with two shape parameters and the Band model with three shape parameters, respectively. It is found that these FRED pulses are distinguished both temporally and spectrally from those in the long-lag pulses. In contrast to the long-lag pulses, only one parameter pair indicates an evident correlation among the five parameters, which suggests that at least four parameters are needed to model burst temporal and spectral behavior. In addition, our studies reveal that these FRED pulses have the following correlated properties: (1) long-duration pulses have harder spectra and are less luminous than short-duration pulses and (2) the more asymmetric the pulses are, the steeper are the evolutionary curves of the peak energy ($E_p$) in the $v/f_v$ spectrum within the pulse decay phase. Our statistical results give some constraints on the current GRB models.

Key words: gamma-ray burst: general – methods: statistical

1. INTRODUCTION

The temporal profiles of gamma-ray bursts (GRBs) are very diverse in morphology but the spectra can be fitted with a simple single Band model (Band et al. 1993). The spectral parameters (the power-law indices and the peak energy in the $v/f_v$ spectrum) are then used to infer the GRB emission and particle acceleration mechanisms. However, the signatures of the gamma-ray epoch of the burst are hidden in the time evolution of the light curve and in its spectral behavior. The individual emission episodes (pulses) that complex light curves are believed to consist of reflect the behavior of a central engine. Due to the overlapping of pulses in most bursts, especially bright ones, only a small fraction of all bursts consist of a long, smooth, and well-shaped pulse, often with a fast rise and an exponential decay (FRED), while others exhibit very complex and jagged light curves. Therefore, an accurate study of individual pulse behavior is often difficult. However, some dimmer bursts with lower signal-to-noise ratios usually have simpler temporal structures that may be easy to model (Norris et al. 2005, hereafter Paper I). Investigations of these pulses are useful and might lead to a deeper understanding of the creation of gamma rays by giving clues to and constraining physical models.

Many authors have studied the temporal and spectral properties of long-duration ($T_{90} > 2$ s) GRB pulses, and a number of characteristics of these pulses have been revealed. The impressive results include, e.g., (1) the temporal asymmetry of pulses in GRBs (that is, longer decay than rise rates), (2) hard-to-soft spectral evolution, and (3) energy dependence of the pulse duration, broadening at lower energies (e.g., Norris et al. 1996; Ryde 2005; Golenetskii et al. 1983; Borganovo & Ryde 2001; Kouveliotou et al. 1993).

However, most of these studies focus on the pulses in bright bursts. Stern et al. (1999) investigated a complexity–brightness correlation in GRBs and found that the average profiles of dim bursts were less complex than those of bright bursts. Based on this, Norris et al. (2005, Paper I) analyzed the temporal and spectral behavior of some long-lag bursts, which tend to be dim but also have relatively simple temporal structures. They found that pulses in long-lag bursts are distinguished both temporally and spectrally from those in bright bursts: (1) the pulses in the long-lag bursts are few in number, (2) the durations are $\sim 100$ times wider (tens of seconds) than those of bright bursts, (3) the peak energy $E_p$ in the $v/f_v$ spectrum is lower, and (4) the long-lag bursts have harder low-energy spectra and softer high-energy spectra.

Kocevski et al. (2003) analyzed the time profiles of 76 FRED pulses with peak fluxes greater than those of long-lag pulses. They only considered the temporal behavior of these pulses and did not analyze the spectral properties. Employing this sample, Peng et al. (2009a, hereafter Paper II) studied the spectral behavior of FRED pulses that are bright enough for spectral analysis to be performed. They focused their attention on the evolutionary slope of the peak energy $E_p$ within the pulse decay phase and found that the slope is correlated with several spectral parameters.

In this work, we would like to employ the sample presented in Paper II to investigate the temporal and spectral properties of these FRED pulses. Discovering if these bursts with FRED pulses are temporally and spectrally distinguished from long-lag bursts is another motivation. In Section 2, we present the sample description. The temporal and spectral profile analysis is given in Section 3. Our discussion and conclusions are presented in the last section.

2. SAMPLE DESCRIPTION

Paper II used two samples provided by Kocevski et al. (2003) and Norris et al. (1999) to investigate the evolutionary slope of $E_p$ in FRED pulses. The main selection criteria for the two samples of Paper II are as follows: (1) the data are provided by
the BATSE instruments on board the Compton Gamma Ray Observatory and the duration is greater than 2 s \((T_\text{90} > 2 \text{ s})\); (2) they exhibit clean, single-peaked events or, in the case of multi-peaked bursts, pulses that are well distinguished and separable from each other; (3) the peak flux is greater than 1.8 photon cm\(^{-2}\) s\(^{-1}\) on a 256 ms timescale. The time-resolved and time-integrated spectra of the two samples were fitted with the Band and Compton models, respectively. Based on these fitting parameters, Paper II studied the evolutionary slope of \(E_p\) as well as the correlations between the slope and the spectral parameters. This analysis showed that the two samples share approximately the same statistical properties, which can be found from Figures 1–9 in Paper II (for more details of the samples and the spectral modeling, one can refer to Kocevski et al. 2003; Norris et al. 1999; Paper II). Therefore, in this paper, we only select the sample fitted by the Band model to investigate the temporal and spectral characteristics of FRED pulses; this sample includes 56 single pulses.

3. TEMPORAL PROFILE AND TIME-INTEGRATED SPECTRAL ANALYSIS

3.1. Temporal Profile Analysis

Once the pulses have been selected we use the pulse model of Paper I to fit them. The pulse model can be rewritten as

\[
I(t) = A\lambda \exp(-\tau_1/(t - t_s) - (t - t_s)/\tau_2),
\]

where \(t\) is time since trigger, \(A\) is the pulse amplitude, \(t_s\) is the pulse start time, \(\tau_1\) and \(\tau_2\) are the characteristics of the pulse rise and the pulse decay, and \(\lambda = \exp[2(\tau_1/\tau_2)]^{1/2}\).

Similar to Peng et al. (2006, 2009b) and Hakkila et al. (2008), we also use the nonlinear least-squares routine MPFIT to fit these pulses. It is based on the well-known and tested MINPACK-1 FORTRAN package of routines available at http://www.netlib.org. Moreover, MPFIT functions permit us to fix any function parameters, as well as to set simple upper and lower parameter bounds. To obtain an intuitive view of the result of the fit, we develop and apply an interactive IDL routine for fitting pulses in bursts, which allows the user to set and adjust the initial pulse parameters manually before allowing the fitting routine to converge on the best-fitting model via the reduced \(\chi^2\) minimization. The background-subtracted light curves combined four channels that are fitted with the pulse model. The fits are examined many times to ensure that they are indeed the best ones. Fits with \(\chi^2\) per degree of freedom larger than 2.5 are rejected. In the end, there are 52 pulses that are included in our sample.

Figure 1. Plots of the fit result of two pulses with the largest value of \(\chi^2\) (left panel) and with the smallest value of \(\chi^2\) (right panel) in our sample.

We demonstrate two fit results with the largest value of \(\chi^2\) (GRB 980301: BATSE trigger 6621) and with the smallest value (GRB 931128: BATSE trigger 2665) in Figure 1. The distributions of \(\chi^2\) per degree of freedom for our sample are displayed in Figure 2. The narrow distribution of the \(\chi^2\) values indicates that the two-exponential model is sufficient to model the pulse light curves.

According to the fitted parameters we can obtain the two shape parameters, width \(w\) and asymmetry \(k\). Following Paper I, we find the pulse width measured between the two 1/e intensity points, \(w = \Delta t_{1/e} = t_2(1 + 2 \ln \lambda)^{1/2}\). The form of the pulse asymmetry \(k = t_2/w\). Quilligan et al. (2002) found that the FWHM of the GRB pulse is a log-normal distribution. It is found that the distribution of \(w\) is also log-normal (see Figure 3) but the distribution of \(k\) is normal (Figure 3). The parameters of the best log-normal and normal fits are given in Table 1.

In addition, we find no significant correlation between the width and asymmetry, which is consistent with the result of the long-lag pulses. The widths of these FRED pulses are

![Histograms for the distribution of \(\chi^2\) in our sample.](image)

**Table 1**

| Property          | FRED Pulse | Long-lag Pulse* |
|-------------------|------------|-----------------|
| \(w \text{ (s)}\) | 6.74 ± 2.47 | 15.18 ± 13.75   |
| \(k\)             | 0.44 ± 0.13 | 0.40 ± 0.19     |
| \(E_p \text{ (keV)}\) | 158.49 ± 79.67 | 109.89 ± 64.50 |
| \(\alpha\)        | -0.89 ± 0.52 | -0.46 ± 0.65    |
| \(\beta\)         | -2.60 ± 0.37 | -2.74 ± 0.25    |

*Reference for the long-lag pulse data: Norris et al. (2005, Paper I).
Figure 3. Distributions of the pulse width $w$ (left panel) and pulse asymmetry $k$ (right panel) in our sample, where the curves represent the Gaussian fit to the two distributions.

Figure 4. Distributions of the pulse peak energy $E_p$, low-energy index $\alpha$, and high-energy index $\beta$ in our sample, where the curves represent the Gaussian fit to the two distributions.

distinguished from the long-lag pulses since the analysis of the long-lag pulse performed in Paper I showed that the average width is larger than 10 s whereas the difference of the mean value of the asymmetry between the FRED pulses and the long-lag pulses is not evident (see Table 1). Actually, considering the standard deviations ($\sigma$) and the number of pulses in each sample (#52 FREDs and #35 long-lag from Paper I) the mean $k$’s are within 1 standard error of the sample mean. In other words, they are equal within uncertainties.

3.2. Spectral Profile Analysis

Paper II detailed the spectral modeling for the single pulses and analyzed the evolutionary slope, $S$, during the decay phase of the FRED pulses. In addition, it examined the relations between the spectral parameters and $S$. In this section, let us first check the distributions of the time-integrated spectral parameters for our sample. Figure 4 shows the distributions of the spectral parameters, $E_p$, $\alpha$, and $\beta$. The corresponding mean value and the standard deviation are listed in Table 1. Note that the spectral parameters come from spectra integrated over a FRED pulse rather than an entire burst.

The previous study showed that the distribution of $E_p$ integrated over a burst is best described by a log-normal distribution (Quilligan et al. 2002). We find that the $E_p$ distribution for the single pulses is also log-normal. Compared with long-lag pulses, the $E_p$ of the FRED pulse is much greater (see Table 1). For the low-energy index the distribution is approximately normal and the spectra of most of the FRED pulses are much steeper than those of the long-lag pulses whereas for the high-energy index the spectra of most of the FRED pulses are a little flatter than those of the long-lag pulses (see Table 1).

3.3. The Relation Between the Temporal and Spectral Parameters

Paper I examined the relations between the temporal and spectral parameters and showed that (1) no clear correlation between the low-energy index $\alpha$ and the pulse width $w$ is indicated, (2) there is a suggestion that $\alpha$ is correlated with pulse asymmetry, (3) the $E_p$ appears to be uncorrelated with any temporal parameters, and (4) neither of the two temporal parameters is correlated with the high-energy index $\beta$. We re-examine the relations and find that the results are also established.
GRBs (Paper I). The first difference is the relation between
for our sample except for two differences from the long-lag pulse
Figure 5. Spectral shape parameter $\alpha$ vs. pulse width $w$ (left panel) as well as $\alpha$ vs. pulse asymmetry $k$ (right panel), where the long dashed lines represent the best-fitting lines.

Table 2

| Parameter Pair | $R_S$ | $P_S$ |
|----------------|-------|-------|
| $w-\alpha$    | 0.49  | 0.0006|
| $k-\alpha$    | -0.0018 | 0.99 |
| $w-S$         | -0.28 | 0.04  |
| $k-S$         | 0.49  | $<10^{-4}$ |
| $w-F$         | -0.53 | $<10^{-4}$ |
| $k-F$         | -0.17 | 0.22  |

for our sample except for two differences from the long-lag pulse GRBs (Paper I). The first difference is the relation between $\alpha$ and $w$. A correlated relation between them is suggested for our sample (see Figure 5 and Table 2). The second difference is that there seems to be no correlation between $\alpha$ and $k$ (see Figure 5 and Table 2). The other parameter pairs, $E_p$ versus $\alpha$, $E_p$ versus $\beta$, $E_p$ versus $w$, $E_p$ versus $k$, $\alpha$ versus $\beta$, $w$ versus $\beta$, and $k$ versus $\beta$, are not correlated with each other.

Paper II studied the relations between the decay slope of the pulse, $S$, and the spectral parameters. In this work, we mainly check the relations between $S$ and the two temporal parameters and between the photon flux and the temporal parameters.

Figure 6 (left panel) shows the relation between $S$ and $w$. An anti-correlation between them is identified for our samples (see also Table 2). In addition, a correlation between $S$ and pulse asymmetry $k$ is suggested in Figure 6 (right panel) and Table 2. Figure 7 shows a similar picture for the photon flux versus two temporal parameters. A clear correlated relation between the photon flux and $w$ is identified, but there seems to be no evident correlation between the photon flux and $k$ (see also Table 2).

Based on the above analysis, the five fundamental temporal and spectral shape parameters $w$, $k$, $\alpha$, $\beta$, and $E_p$ do not show compelling evidence for any pairwise correlation, except for a correlation between $w$ and $\alpha$. This implies that at least four independent physical parameters are required to determine pulse behavior in the energy band $\sim 25-2000$ keV, which is different from that of the long-lag pulse investigated in Paper I.

4. DISCUSSION AND CONCLUSIONS

By studying the temporal and spectral characteristics of the FRED GRB pulses we first show that the FRED pulse is temporally and spectrally distinct from that of the long-lag pulse: (1) the average width of the FRED pulses (8.75 s) is below the corresponding values of the long-lag one (the average width is above 10 s; Paper I); (2) the average peak energy, $E_p$, in the $v f_\nu$ is 158 keV which is also greater than the long-lag pulse (110 keV); (3) the low-energy indices obtained from FRED pulses are softer than those from long-lag pulses; (4) the high-energy indices of FRED pulses are slightly harder than those of long-lag pulses. Therefore, the long-lag, wide-pulse GRBs and the general sample of GRB pulses may represent a different sub-class with generally different physical properties. But the difference in the pulse asymmetry between the FRED and long-lag pulses is not significant.

An analysis of the relations between the temporal and spectral shape parameters suggests that they have no visible correlation except that the pulse width is correlated with the lower-energy index $\alpha$, which indicates that at least four parameters are needed to model burst temporal and spectral behavior. The inconsistency of correlations between $w$ and $\alpha$ as well as pulse asymmetry $k$ and $\alpha$ with that of the long-lag burst studied in Paper I may be caused by the sample size. Our sample, consisting of 52 pulses, is a factor of two larger than that of the long-lag bursts. Ryde et al. (2005) and Ryde (2005) showed a similar relation that hard spectra (with large spectral power-law indices $\alpha$) give the largest lags. Moreover, Paper I pointed out that the pulse width is strongly correlated with spectral lag and these two parameters may be viewed as mutual surrogates. If this is the case, we tend to believe that there is indeed a correlation between $w$ and $\alpha$. Our analysis confirms that $k$ is not correlated with $\alpha$. Another possibility is that the characteristics of the FRED pulses are indeed different from the long-lag pulses as shown above.

The anti-correlation between $w$ and the photon flux shown in our analysis is also well established. It is another property of the pulse rather than the bursts themselves. Ryde (2005) found an inverse relation between flux and lag. It is interesting that the three quantities correlate with each other. If the pulse width and the spectral lag can be viewed as mutual surrogates indeed the anti-correlated relation between $w$ and the photon flux must be established. A similar result given by Hakkila et al. (2008) indicated that there is a correlation between the pulse duration $w$ and the isotropic pulse peak luminosity. These pulse properties may provide a useful constraint on the theoretical model. Therefore, the correlation flux versus $w$ shown in Figure 7 is established in our sample.

The correlation flux versus $w$ shown in Figure 7 seems neat, and we might suspect that it is just the result of a selection bias since other pulses, such as short-lag dim pulses, are likely
underrepresented. Paper I examined the fluence hardness ratios integrated over the whole burst, with the split at $\tau_{\text{lag}} < 1 \text{s}$ in the range $0.5 < F_{\text{peak}} < 2.0$ to see if there is any difference between long-lag and short-lag dim bursts. They found that the short-lag dim bursts have slightly harder spectra than the long-lag dim bursts in the same peak flux range. The analysis of Shahmoradi & Nemiroff (2010) showed that simple hardness ratios are good estimators for the spectral peak energy in GRBs independent of the type of the burst, whether it is a long-duration GRB or a short-duration one. So, the short-lag dim bursts should have greater peak energy than the long-lag dim bursts whereas the mean peak energies of the burst spectra are correlated with intensity (flux): lower intensity groups of burst spectra exhibit a lower average peak energy (Mallozzi et al. 1995). Hence, it is suggested that the short-lag dim bursts with greater peak energy might have a higher intensity. Although the above properties of correlation are for bursts rather than pulses we still think that the correlation should exist among pulses since Borgonovo & Björnsson (2006) showed that the overall properties of a burst are determined mainly by the properties of pulses. Therefore, we tend to believe it is not a selection bias even if we cannot test this with a short-lag dim pulse sample.

The evident anti-correlation between the evolutionary slope during the pulse decay phase and pulse asymmetry seems to show pulses with short rises, and very long decay times tend to show slower decay of $E_p$. The tendency appears to suggest that the pulses might represent external shocks capable of initiating afterglow (Hakkila et al. 2008).

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