Dependence of Temporal Properties on Energy in Long-Lag, Wide-Pulse Gamma-Ray Bursts

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Abstract

We employed a sample by Norris et al. (2005, ApJ, 625, 324) to study the dependence of the pulse temporal properties on energy in long-lag, wide-pulse gamma-ray bursts. Our analysis shows that the pulse peak time, rise time scale, and decay time scale are power-law functions of energy, which is a preliminary report on the relationships between the three quantities and energy. The power-law indexes associated with the pulse width, rise time scale, and decay time scale are correlated, and the correlation between the indexes associated with the pulse width and the decay time scale is more obvious. In addition, we have found that the pulse peak lag is strongly correlated with the CCF lag, but the centroid lag is less correlated with the peak lag and the CCF lag. Based on these results and some previous investigations, we tend to believe that all energy-dependent pulse temporal properties may come from the joint contribution of both the hydrodynamic processes of the outflows and the curvature effect, where the energy-dependent spectral lag may be mainly dominated by the dynamic process, and the energy-dependent pulse width may be mainly determined by the curvature effect.

Key words: gamma rays: bursts — method: statistical

1. Introduction

Cosmic gamma-ray bursts (GRBs) exhibit a great diversity of the temporal and spectral structure, and their origin and mechanism are still unclear. In many bursts the temporal activity is suggestive of a stochastic process. It was suggested that some simple bursts with well-separated structure might consist of fundamental units of emission, such as pulses, with some of them being seen to comprise a fast rise and an exponential decay (FRED) (see, e.g., Fishman et al. 1994). The temporal and spectral properties of these fundamental pulses might give us valuable clues about the origin of these events, and will provide powerful constraints on the detailed physical process.

Recently, the temporal and spectral characteristics of GRB pulses have been intensively studied, and several significant correlations between them have been found. Norris et al. (1986) first noted that GRB pulses have an observed trend of hard to soft spectral evolution. This has been confirmed by many other authors (see, e.g., Bhat et al. 1994; Norris et al. 1996; Band 1997). The hard-to-soft spectral evolution is associated with two distinct, observed features: pulse peaks shift to later times and pulses become wider at lower energies (e.g., Link et al. 1993; Norris et al. 1996, 2000, 2005, last one hereafter N05). By using the average autocorrelation function and the average pulse width, Fenimore et al. (1995) showed that a narrowing of the pulse width with energy well follows a power law, with an index of \( -0.4 \). This is the first quantitative relationship between the temporal and spectral structures in GRBs. Norris et al. (1996) proposed a “pulse paradigm”, and found that the average raw pulse shape dependence on energy is also approximately a power law, consistent with an autocorrelation analysis of Fenimore et al. (1995). This was further confirmed by later studies (Piro et al. 1998; Costa 1999; Nemiroff 2000; Feroci et al. 2001; Crew et al. 2003; Qin et al. 2004, 2005; Peng et al. 2006).

In the standard fireball scenario, it was suggested that the process of radiation in GRBs is most likely to be through synchrotron emission (see, e.g., Katz 1994; Sari et al. 1996). The power-law dependence of the pulse width on energy has led to a suggestion that this relationship could be related to synchrotron radiation (Fan et al. 1995; Cohen et al. 1997; Piran 1999). Kazanas, Titaruchuk, and Hua (1998) proposed that the result could be accounted for by synchrotron cooling (see also Chiang 1998; Dermer 1998; Wang et al. 2000). It was suspected that the power-law relationship might result from a relative projected speed or a relative beaming angle (Nemiroff 2000). Recently, it has also been argued that the relativistic curvature effect could lead to the power-law relationship (Qin et al. 2004, 2005; Shen et al. 2005; Peng et al. 2006). Dado, Dar, and De Rújula (2007) suggested that such a correlation is a straightforward prediction of the ‘cannonball’ model of GRBs (Dar & De Rújula 2004).

The phenomenon of GRB pulse peaks evolving from higher to lower energies is a prevalent property of most bursts. Many authors generally analyze the time delay between the light curves in different energy bands. Using a cross-correlation method, Cheng et al. (1995) first found that soft emission had
a time delay relative to high-energy emission, and quantified the delay. Subsequently, several investigations on the GRB lag have been carried out (Norris et al. 1996, 2000; Wu & Fenimore 2000; Hakkila & Giblin 2004, 2006; Chen et al. 2005; Norris & Bonnell 2006; Yi et al. 2006; Z. Zhang et al. 2006; Z.-B. Zhang et al. 2006). There have been several attempts to explain the origin of the time lag. It was suggested that the activity of the central engine and the hydrodynamic time-scale of the internal shocks might produce the time lag (e.g., Daigne & Mochkovitch 1998, 2003; Wu & Fenimore 2000). Ioka and Nakamura (2001) proposed that the lag was caused by the viewing angle of the jet. Another possible origin of the lag was proposed to be radiative cooling (e.g., Zhang et al. 2002; Bai & Lee 2003; Schaefer 2004). Kocevski and Liang (2003) assumed that the observed lag was a direct result of spectral evolution (see also Ryde 2005). Shen, Song, and Li (2005) argued that the observed lags could be accounted for by the curvature effect of fireballs (see also Lu et al. 2006a).

Kocevski, Ryde, and Liang (2003) found that there is a linear relationship between the pulse rise time and the pulse width (see figure 10 in the paper). The same result was also found in GRB pulses observed by INTEGRAL (see figure 5a in Ryde et al. 2003). Recently, a strong correlation between the pulse rise time and the pulse width in different energy channels was presented by N05. They fitted the two quantities with a power-law function, and found that the slope increases from 0.7 to 1.0 as the energy channel increases, and that the correlation is the tightest in channel 3 (100–300 keV). Lu, Qin, and Yi (2006a) further studied the relationship between the two quantities, and proposed that merely the curvature effect could reproduce the correlation.

Although a power-law anti-correlation between the pulse width and the energy, a strong correlation between the pulse rise time and the pulse width, and pulse peaks evolving in time from higher to lower energies in many GRBs have been studied by many authors, it is unclear how the pulse peak time, rise time scale, and decay time scale depend on energy. Recently, Liang et al. (2006) have tentatively investigated the correlation between the peak time and the average photon energy for GRB 060218, which has the longest pulse duration and spectral lag observed to date among the observed GRBs, and found that $t_{\text{peak}} \propto E^{-0.25\pm0.05}$. It is known that most bright bursts have many narrow pulses that are difficult to model due to overlapping. However, the relatively simple, long spectral lag, wide-pulse bursts are easier to model and might have simpler physics. Since the pulses in long-lag bursts are very long, a sufficient pulse definition is available, which makes the study easier. N05 analyzed the temporal and spectral behaviors of wide pulses in 24 long-lag bursts, using a pulse model with two shape parameters, width and asymmetry, and the Band spectral model with three shape parameters. They found that the five descriptors are essentially uncorrelated, but the pulse width is strongly correlated with the spectral lag. They also found that pulses in long-lag bursts are distinguished from those in bright bursts: pulses in long spectral lag bursts are fewer in number and $\sim 100$-times wider (tens of seconds), have systematically lower peaks in $nF_{\nu}$, and have significantly softer spectra.

As discovered in Norris (2002), the proportion of long-lag, wide pulses within long-duration bursts increases from negligible among bright BATSE bursts to $\sim 50\%$ at the trigger threshold. Long-lag bursts appear to be important, since these bursts may form a separate subclass of GRBs (Liang et al. 2007), and have a relatively simple physical mechanism. Based on the fact that the redshifts of three such bursts are available [GRB 980425 (Galama et al. 1998), GRB 031203 (Malesevi et al. 2004), and GRB 060218 (Mirabal et al. 2006)], it was argued that long-lag bursts are probably relatively nearby, and the local event rate of these GRBs should be much higher than that expected from the high-luminosity GRBs (Liang et al. 2007; Cobb et al. 2006; Pian et al. 2006; Soderberg et al. 2006). It was suggested that their wide-pulse, long-lag, and under-luminous features are partly attributed to the off-axis viewing angle effect (Nakamura 1999; Salmonson 2000; Ioka & Nakamura 2001), and partly due to their lower Lorentz factors (Kulkarni et al. 1998; Woosley & MacFadyen 1999; Salmonson 2000; Dai et al. 2006; Wang et al. 2007). Recently, it was argued that they might have a different type of central engine (e.g., neutron stars rather than black holes) from bright GRBs (Mazzali et al. 2006; Soderberg et al. 2006; Toma et al. 2007).

In the present work, we employed the long-lag burst sample investigated in N05 to analyze the dependence of their temporal properties on energy. We describe the sample and data in section 2. The results are presented in section 3, followed by conclusions in section 4.

### 2. Sample and Data Description

The GRB sample employed was that presented in N05, where the bursts are found to consist of a few long-lag, wide, well-defined pulses. The data were provided by the BATSE instruments on board the CGRO spacecraft. In this sample, an obvious migration of the peaks of the pulses at different energies can be observed. The bursts of the sample are from 1429 BATSE events described in Norris (2002), with the criterion that $T_{90} > 2$ s, $F_{\text{peak}} > 0.75$ photons cm$^{-2}$ s$^{-1}$ (50–300 keV), peak intensity $P > 1000$ counts s$^{-1}$ (> 25 keV), and average lag $> 1$ s. In addition, only those bursts with sufficiently non-overlapping pulses were considered. The sample consisted of 24 bursts, most of which contained single pulses. (For more details of the sample selection, see N05.)

For the purpose of fitting a pulse, N05 developed a pulse model with a form containing two exponentials, one increasing and one decreasing with time. This pulse model is written as

$$I(t) = A \lambda / [\exp(t_{1}/t \exp(t_{2}/t_{2})],$$

where $\lambda = \exp[2(t_{1}/t_{2})^{1/2}]$, $A$ is the pulse peak intensity, and $t_{1}$ and $t_{2}$ are the two fundamental timescales dominating the rise and decay rates, respectively. The time of pulse onset with respect to $t = 0$, $t_{\text{on}}$, was ignored. The 24 long-lag bursts were fitted with this model in N05. The parameter values for all identified pulses were obtained, including the pulse peak intensity ($A$), pulse onset time ($t_{\text{on}}$), effective onset time ($t_{\text{eff}}$), and peak time ($t_{\text{peak}}$), as well as the two fundamental timescales ($t_{1}$ and $t_{2}$), width ($w$), and asymmetry ($k$) (see table 2 in N05). The corresponding errors were also estimated. The effective onset time, $t_{\text{eff}}$, is defined as the time when the pulse reaches 0.01 times of the peak intensity. Both onset times are relative to the burst trigger...
time. The peak time is defined as that relative to the effective onset time.

3. Results

Due to a variety of interpretations of the spectral lag observed in GRBs, we suspect that the quantity might be contributed by various effects. The most important one might be the mechanisms of shocks, which are likely to dominate the light curves of pulses in their rise phase. Another important factor might be the curvature effect, which seems to dominate the decay phase of pulses (see, e.g., Qin & Lu 2005). We thus pay attention to how the pulse peak time, rise and decay time scales depending on energy, while checking if the dependence is the same or different.

3.1. Dependence of Pulse Peak Time, Rise Time, and Decay Time Scales on Energy

To investigate this issue, let us define three quantities: the pulse peak time position \( t_{\text{p}} \), pulse rise time scale \( \Delta t_{\text{r}} \), and pulse decay time scale \( \Delta t_{\text{d}} \), where \( t_{\text{p}} \) is defined as the time between the pulse peak and the pulse onset, \( \Delta t_{\text{r}} \) and \( \Delta t_{\text{d}} \) are defined as the time between the pulse peak and the two 1/\( e \) intensity points respectively as those defined in N05. (Note that \( \Delta t_{\text{r}} \) and \( \Delta t_{\text{d}} \) are close to the FWHMs in the rising phase and decaying phase, respectively, since \( 1/\epsilon \) is close to 1/2.) In addition, according to their definitions, \( \Delta t_{\text{r}} = t_{\text{rise}} \) and \( \Delta t_{\text{d}} = t_{\text{dec}} \), where \( t_{\text{rise}} \) and \( t_{\text{dec}} \) are the pulse rise and decay timescales defined in N05, respectively.) The onset time, \( t_{\text{on}} \), defined here is the time (relative to the burst trigger time) when the total counting rate of all four energy channels (25–50, 50–100, 100–300, and > 300 keV) reaches 0.01 times the peak intensity in a single-pulse burst. With this definition, the pulse peak time positions, \( t_{\text{p}} \), in the different channels for a burst are relative to the same reference time (the onset \( t_{\text{on}} \)). We thus can directly compare them (or, the shifts of the pulse peaks with respect to the different channels can be easily estimated).

The \( t_{\text{peak}} \) values listed in table 2 of N05 are relative to \( t_{\text{on}} \), which is the geometric mean of the lower and upper boundaries of the channel (here we use 300–1000 keV for channel 4, which is adopted throughout this paper). This method of analysis was generally adopted in previous works (see, Fenimore et al. 1995; Norris et al. 1996; N05). Let \( \alpha_{\text{r}}, \alpha_{\text{w}}, \alpha_{\text{d}}, \) and \( \alpha_{\text{d}} \) denote the indices of the power-law relationships between \( t_{\text{r}} \), \( \Delta t_{\text{r}} \), \( \Delta t_{\text{f}} \), and \( \Delta t_{\text{d}} \) and energy, respectively. Displayed in figure 2 are the distributions of these indices. We fit them with Gaussian profiles. The values of the fit (the value and the standard deviation) as well as the medians of the distributions of the four power-law indices are listed in table 1. [For the distribution and other analysis of \( \alpha_{\text{w}} \), see also Jia and Qin (2005); Peng et al. (2006).] One can find from figure 2 and table 1 that the distributions of these indices have large dispersions. This implies that the energy dependence of the temporal properties may not be the same for different bursts. It is interesting that the distribution of \( \alpha_{\text{d}} \) is obviously narrower than that of other indices (see table 1). A possible interpretation of this phenomenon is that the mechanism causing the dependence of the rise time scale on energy might be somewhat similar for different bursts.

In an analysis of the relationship between the pulse width and energy, one generally studied the dependence of the average pulse width on energy for the adopted samples (see, for example, Fenimore et al. 1995; Norris et al. 1996; N05). Here, we also calculated the dependence of the average values of \( t_{\text{p}}, \Delta t_{\text{r}}, \) and \( \Delta t_{\text{d}} \) on energy. For the sake of comparison, the energy dependence of the average value of \( \Delta t_{\text{w}} \) is displayed

\[ \Delta t_{\text{w}} = \frac{1}{\Delta t_{\text{r}}} + \frac{1}{\Delta t_{\text{d}}} \]

in N05; the 24 pulses in different energy channels from that table via a simple derivation. Listed in table 2 of N05 is also the effective onset time \( t_{\text{eff}} \) defined in that paper, which is relative to the trigger time, for each pulse in each channel. With \( t_{\text{eff}} \) and \( t_{\text{peak}} \), we were able to determine the pulse peak time relative to the trigger time. We combined the 64 ms count data from all four channels (the data are available via anonymous ftp in the website\(^1\) to obtain the “bolometric” light-curve profile, and derived our onset time, \( t_{\text{on}} \), for each burst by fitting the light curve with the method of N05, where the adopted pulse model was equation (1) of the paper. Shifting \( t_{\text{peak}} \) from \( t_{\text{eff}} \) to \( t_{\text{on}} \) yielded the pulse peak time \( t_{\text{p}} \) defined in this paper. The correspondent uncertainties were calculated using the error transfer formula.

Illustrated in figure 1 are \( t_{\text{p}}, \Delta t_{\text{r}}, \) and \( \Delta t_{\text{d}} \) of individual pulses in each energy channel. To compare with the dependence of the pulse width on energy, the value of \( \Delta t_{\text{w}} \), which is defined as the time between the two 1/\( e \) intensity points of individual pulse, as that defined in N05 (\( \Delta t_{\text{w}} = w \)), of each pulse is also displayed in figure 1. The figure clearly shows that \( t_{\text{p}} \) generally migrates to later times at lower energy channels, and \( \Delta t_{\text{r}}, \Delta t_{\text{f}}, \) and \( \Delta t_{\text{d}} \) become wider at lower energy bands (in several exception cases, the data points are well inside the corresponding trend within 1σ errors).

According to figure 1, we assume that the four time quantities \( t_{\text{p}}, \Delta t_{\text{w}}, \Delta t_{\text{r}}, \) and \( \Delta t_{\text{d}} \) are power-law functions of energy. The dependence of the four time quantities on energy is parameterized by the power law index, which is obtained by fitting the data points of each quantity in the four energy channels with a power law. The energy adopted for a channel is the geometric mean of the lower and upper boundaries of the channel (here we use 300–1000 keV for channel 4, which is adopted throughout this paper). This method of analysis was generally adopted in previous works (see, Fenimore et al. 1995; Norris et al. 1996; N05). Let \( \alpha_{\text{r}}, \alpha_{\text{w}}, \alpha_{\text{d}}, \) and \( \alpha_{\text{d}} \) denote the indices of the power-law relationships. Displayed in figures 1 and 2 are the distributions of these indices. We fit them with Gaussian profiles. The values of the fit (the value and the standard deviation) as well as the medians of the distributions of the four power-law indices are listed in table 1. [For the distribution and other analysis of \( \alpha_{\text{w}} \), see also Jia and Qin (2005); Peng et al. (2006).] One can find from figure 2 and table 1 that the distributions of these indices have large dispersions. This implies that the energy dependence of the temporal properties may not be the same for different bursts. It is interesting that the distribution of \( \alpha_{\text{d}} \) is obviously narrower than that of other indices (see table 1). A possible interpretation of this phenomenon is that the mechanism causing the dependence of the rise time scale on energy might be somewhat similar for different bursts.

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\[ \Delta t_{\text{w}} = \frac{1}{\Delta t_{\text{r}}} + \frac{1}{\Delta t_{\text{d}}} \]

1) ftp://cossc.gsfc.nasa.gov/compton/data/batse/.

Downloaded from https://academic.oup.com/pasj/article-abstract/59/4/857/1489877

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Fig. 1. Energy vs. pulse peak time (asterisk), pulse width (cross), pulse rise time scale (open triangle), and pulse decay time scale (open square) for all the 24 pulses studied in this paper, where \( E \) is the geometric means of the lower and upper channel boundaries, \( t_i \) represents \( t_p, \Delta t_w, \Delta t_r, \) and \( \Delta t_d \). Symbols joined by line segments correspond to the same time quantity in the different energy channels.

as well (we include only those bursts with their pulse signal being detectable in all four channels; the burst of #6526, which has a very long timescale, is excluded throughout the paper). Plotted in figure 3 are the relationships between the average values of \( t_p, \Delta t_w, \Delta t_r, \Delta t_d, \) and energy. The regression analysis yields: 

\[
\log t_p = (1.45 \pm 0.26) - (0.25 \pm 0.14) \log E,
\log \Delta t_w = (2.15 \pm 0.09) - (0.45 \pm 0.05) \log E,
\log \Delta t_r = (1.40 \pm 0.10) - (0.37 \pm 0.05) \log E,
\log \Delta t_d = (2.08 \pm 0.09) - (0.48 \pm 0.05) \log E.
\]

3.2. Relationships between Power-Law Indices

Because power-law indices act as an active factor reflecting the relationship between the temporal and spectral properties of pulses, we are curious about how the three power-law indices (\( \alpha_w, \alpha_r, \) and \( \alpha_d \)) that are associated with various widths of pulses are related. Figure 4 shows the relations between them. The results of a correlation analysis for the three quantities are listed in table 2. We find that \( \alpha_w \) and \( \alpha_d \) are highly correlated, while the other pairs of the quantities are obviously less correlated. This suggests that the mechanism causing the power-law relationship between the pulse width and energy is the same as that between the pulse decay time scale and energy. Recall that the distributions of these indices have larger dispersions, which implies that the energy dependence of these temporal properties may not be the same for different bursts. We guess that the energy dependence of the rise time scale and that of the decay time scale for the same burst during the same pulse might share some mechanism, which currently is unclear.
Fig. 2. Distributions of the power-law indices $\alpha_w$ (the first panel), $\alpha_r$ (the second panel), $\alpha_d$ (the third panel), and $\alpha_p$ (the fourth panel) obtained by fitting the pulse width, rise time scale, decay time scale, and peak time and energy with power law functions, respectively. The dashed lines are the best fits by the Gaussian functions.
Table 1. Characteristics of the distributions of the four power-law indices.

| Power-law index | Median $\alpha$ (modeled with a Gaussian profile) | $\sigma$ |
|-----------------|-------------------------------------------------|---------|
| $\alpha_p$      | -0.27 $\pm$ 0.04                               | 0.45 $\pm$ 0.08 |
| $\alpha_w$      | -0.39 $\pm$ 0.04                               | 0.51 $\pm$ 0.11 |
| $\alpha_r$      | -0.35 $\pm$ 0.03                               | 0.19 $\pm$ 0.02 |
| $\alpha_d$      | -0.37 $\pm$ 0.06                               | 0.40 $\pm$ 0.06 |

Table 2. Correlations of the three power-law indices.

| Correlation       | Spearman correlation coefficient $(r)$ | Probability $(p)$ |
|-------------------|----------------------------------------|------------------|
| $\alpha_r = (0.03 \pm 0.02) + (0.85 \pm 0.03) \alpha_w$ | 0.77             | $5.1 \times 10^{-5}$ |
| $\alpha_d = (-0.01 \pm 0.01) + (1.05 \pm 0.03) \alpha_w$ | 0.98             | $2.2 \times 10^{-14}$ |
| $\alpha_d = (0.06 \pm 0.03) + (1.47 \pm 0.07) \alpha_r$ | 0.66             | $1.1 \times 10^{-3}$ |

Fig. 3. Average pulse peak time (filled pentagon), width (filled circle), rise time scale (filled triangle), and decay time scale (filled square) as the functions of energy, where $t_i$ represents the average values of $t_p$, $\Delta t_w$, $\Delta t_r$, and $\Delta t_d$. The solid lines are the best fits.

If this mechanism varies from burst to burst, there would exist a weak correlation between $\alpha_r$ and $\alpha_d$, as observed in figure 4. Shown in other aspects, a correlation analysis between $\Delta t_r$, $\Delta t_d$, and $\Delta t_w$ in different energy channels might be helpful. The results are illustrated in figure 5, which shows that $\Delta t_r$, $\Delta t_d$, and $\Delta t_w$ are correlated, and the strong correlations between $\Delta t_d$ and $\Delta t_w$ exist in each of the three energy channels. This is consistent with previous studies (Kocevski et al. 2003; Ryde et al. 2003; Lu et al. 2006a). What are hinted and concluded by the correlation analysis of the indices are reinforced by these new results. One should keep in mind that correlations between different temporal properties might partially (or mainly) be due to the same Lorentz factor for the same pulse (see, Lu et al. 2006a), but the more obvious correlation between $\Delta t_d$ and $\Delta t_w$ than that between other pairs suggests that, besides the Lorentz factor, there must be other factors at work in producing the strong correlation between the two quantities. As shown in Zhang and Qin (2005), the ratio of $FWHM_r$ to $FWHM_d$ is not affected by the Lorentz factor.

One might notice that, in terms of mathematics, the strong correlations between $\alpha_d$ and $\alpha_w$ and between $\Delta t_d$ and $\Delta t_w$ may result from the fact that $\Delta t_w$ is dominated by $\Delta t_d$. Or, in turn, the strong correlations between $\alpha_d$ and $\alpha_w$ and between $\Delta t_d$ and $\Delta t_w$ may confirm the fact. As shown in Qin et al. (2004), the ratio of $FWHM_r$ to $FWHM_d$ would be less than 1.3 for
Fig. 5. Plots of $\Delta t_r$ vs. $\Delta t_w$, $\Delta t_d$ vs. $\Delta t_w$, and $\Delta t_d$ vs. $\Delta t_r$ in the first three energy channels, where subscripts 1, 2, and 3 represent the first channel (the first row), the second channel (the second row), and the third channel (the third row), respectively. The dashed lines are the best fits. The $\Delta t_r$ are well correlated with the $\Delta t_w$ in channels 1, 2, and 3 with the slopes of 0.69, 0.94, and 1.05, and $R = 0.75, 0.87, 0.92$, respectively. The $\Delta t_d$ and $\Delta t_w$ are strongly correlated with the slopes of 1.11, 1.01, and 0.98 and $R = 0.98, 0.98, 0.99$ for channels 1, 2, and 3, respectively. There exist the relatively weak correlations between $\Delta t_d$ and $\Delta t_r$ in channels 1, 2, and 3 with the slopes of 0.74, 0.70, and 0.74, and $R = 0.60, 0.74, and 0.84$, respectively.
pulses arising from the emission of relativistically expanding fireballs. Therefore, it is expected that $\Delta t_w$ might generally be dominated by $\Delta t_d$, as suggested in figure 1.

From figures 2 and 4 one finds that $\alpha_d < \alpha_t$. This suggests that the decay time scale rapidly decreases with respect to energy, while the variance of the rise time scale with an increasing of energy is relatively mild. This implies that the curvature effect plays an important role in the decaying phase of pulses, and that the contribution of the effect makes $\alpha_d$ smaller (see, e.g., Qin et al. 2005; Peng et al. 2006).

3.3. Relationships between Various Spectral Lags and between the Lags and Other Time Scales

N05 measured the peak lags of all pulses between channels 2 and 3 in 24 long-lag bursts, and found that as the pulse width increases, the spectral lag measured between the pulse peaks tends to increase. We found that not only the peak time lag (note that what we measure here is the peak lag between channels 1 and 3, $t_{p,13}$) but also the CCF lag, which is the lag calculated with the cross correlation function (CCF) method, increase with the increasing of the pulse width. The CCF lag used here was also derived between channels 1 and 3, $\tau_{CCF,13}$, which has been extensively studied (Link et al. 1993; Cheng et al. 1995; Norris et al. 1996, 2000; Wu & Fenimore 2000; Hakkila & Giblin 2004, 2006; Chen et al. 2005; Norris & Bonnell 2006; Yi et al. 2006; Z. Zhang et al. 2006; Z.-B. Zhang et al. 2006). Here, we derived the CCF lag from the peak of the CCF without considering the side-lobe contribution of the CCF. Since the light curves are smooth pulses and their lags are significantly larger than the time bin, the peaks of CCFs are robust to estimate the lags. The errors of CCF lags were evaluated by simulations. Besides these two lags, the centroid lag which is the lag of the pulse centroid was discussed in N05, and it was found to be well measured and to be well correlated with the pulse width. It was recently suggested that the correlation might be due to the Lorentz factor (see, e.g. Peng et al. 2007).

To analyze the relationships between the three lags, we calculated the centroid lag between channels 1 and 3 ($\tau_{cen,13}$) as well. The plots of $\tau_{cen,13}$ vs. $t_{p,13}$, $\tau_{cen,13}$ vs. $\tau_{CCF,13}$, and $\tau_{CCF,13}$ vs. $t_{p,13}$ are displayed in figure 6. One finds that $\tau_{cen,13}$ is weakly correlated with both $t_{p,13}$ and $\tau_{CCF,13}$, while the later two are strongly correlated. The best fits to $\tau_{CCF,13}$ and $t_{p,13}$ yield $\log \tau_{CCF,13} = (-0.25 \pm 0.06) + (1.18 \pm 0.11) \log t_{p,13}$. The strong correlation between $t_{p,13}$ and $\tau_{CCF,13}$ and the weak correlations between the two quantities and $\tau_{cen,13}$ suggest that $\tau_{CCF,13}$ is mainly caused by a shifting of the peaks, while $\tau_{cen,13}$ is not. We believe that $t_{p,13}$ and $\tau_{cen,13}$ reflect different aspects of spectral lags, with one representing the shifting of peaks and the other describing an enhancement of the time scale of pulses. We thus propose that, to reveal a spectral lag in detail, both $t_{p,13}$ and $\tau_{cen,13}$ should be measured.

In addition, we find that $\tau_{cen,13}$ is systematically larger than both $t_{p,13}$ and $\tau_{CCF,13}$. According to the above interpretation, this implies that the lag caused by the stretching of pulses is always larger than that caused by the shifting of peaks.

Hakkila and Giblin (2006) found that GRB lags are consistent across a wide range of prompt emission energies, $\log l_{g11} \approx \log l_{g21} + \log l_{g32}$. Under the interpretation proposed above, the three lags ($l_{g11}$, $l_{g21}$, and $l_{g32}$) are mainly due to the shifting of $t_{p}$ in the corresponding channels. Therefore, they could be approximated by $t_{p,13}$, $t_{p,12}$, and $t_{p,23}$, respectively. Meanwhile, according to their definitions, one has $t_{p,13} = t_{p,12} + t_{p,23}$. The relation $l_{g11} \approx l_{g21} + l_{g32}$ is thus explained.

Bhat et al. (1994) found that the time lag between the counting rate and the hardness ratio was directly correlated with the rise time of the burst counting rate profile. Motivated by this, we analyzed the relationships between the three lags and the pulse rise time and decay time scales. The results are displayed in figure 7. It shows that the peak lag and CCF lag are well correlated with the pulse rise time scale and weakly correlated with the pulse decay time scale, which is consistent with that found by Peng et al. (2007). However, the centroid lag is strongly correlated with the pulse decay time scale and weakly correlated with the pulse rise time scale. The latter phenomenon is in agreement with what is interpreted above. As discussed in the last subsection, $\Delta t_w$ is likely to be dominated by $\Delta t_d$. Thus, it is expectable that $\tau_{cen,13}$ is correlated with $\Delta t_d$, since according to this interpretation, the centroid lag reflects the stretching of the pulse width. The correlations between the peak and CCF lags and the pulse rise time scale indicate that the two lags might be caused by some
Fig. 7. Relationships between the three lags and the pulse rise time and decay time scales, where $\Delta t_{r,1}$ and $\Delta t_{d,1}$ are the pulse rise time and decay time scales in channels 1, respectively. The dashed lines are the best fits, where the correlation coefficients of between the peak lag, CCF lag, and centroid lag and the pulse rise time scale are 0.76, 0.71, and 0.54 (the first column), and the pulse decay time scale are 0.39, 0.25, and 0.90 (the second column), respectively.
mechanism associated with the pulse rise time scale. Probably, the peak and CCF lags and the pulse rise time scale might be created mainly by a dynamic process, while the centroid lag and the pulse decay time scale might be formed by both the dynamic process and the curvature effect.

4. Conclusions

Using a sample of 24 long-lag, wide-pulse GRBs described in N05, we investigated the dependence of the pulse temporal properties on energy. It is obvious that the peak time generally migrates to a later time at lower energy channels, and the pulse width, rise time, and decay time scales become wider at lower energy bands. Fitting the average pulse peak time, rise time, and decay time scales with a power-law function of energy yields $t_p \propto E^{-0.25 \pm 0.14}$, $t_r \propto E^{-0.37 \pm 0.05}$, and $t_d \propto E^{-0.48 \pm 0.05}$. This is a preliminary report on the relationships between the three quantities and energy. The three power-law indices ($\alpha_p$, $\alpha_r$, and $\alpha_d$) have large dispersions, and the medians of their distributions are $-0.27$, $-0.35$, and $-0.37$, respectively. It is not surprising since in the well defined power law relationship between the pulse width and energy one also finds a larger dispersion of the index (see also Jia & Qin 2005; Peng et al. 2006). This implies that the energy dependence of the temporal properties may not be the same for different bursts. It is interesting that the distribution of $\alpha_r$ is obviously narrower than that of other indices (see table 1). A possible interpretation of this phenomenon is that the mechanism causing the dependence of the rise time scale on energy might be somewhat similar for different bursts. Liang et al. (2006) noted that the peak time dependence on the average energy (from 0.3–150 keV) in the single pulse burst GRB 060218, detected by Swift, was approximately a power law, and the power law index was $\sim -0.25 \pm 0.05$, which is consistent with our result. This favors what argued by Liang et al. (2006) that this event may be a typical long-lag, wide-pulse burst and share the similar radiation physics with other BATSE bursts.

We also find that the three power-law indices ($\alpha_w$, $\alpha_r$, and $\alpha_d$) are correlated, where $\alpha_w$ and $\alpha_d$ are found to be more obviously correlated. It suggests that the mechanism causing the power law relationship between the pulse width and energy is the same as that between the pulse decay time scale and energy. Recalling that the distributions of these indices have large dispersions, implying that the energy dependence of these temporal properties may not be the same for different bursts, we guess that the energy dependence of the rise time scale and that of the decay time scale for the same burst during the same pulse might share some mechanism that is unclear currently. If this mechanism varies from burst to burst, there would exist a weak correlation between $\alpha_r$ and $\alpha_d$, as observed in figure 4. In addition, we find that the pulse peak lag is strongly correlated with the CCF lag, but the centroid lag is weakly correlated with the peak lag and CCF lag. This suggests that the CCF lag is mainly caused by a shifting of the peaks, while the centroid lag is not. We argue that the peak lag and the centroid lag reflect different aspects of spectral lags, with one representing the shifting of peaks and the other describing the enhancement of the time scale of pulses. We thus propose that, to reveal a spectral lag in detail, both the peak lag and the centroid lag should be measured. Our analysis also shows that the centroid lag is systematically larger than both the peak and CCF lags. According to the above interpretation, this implies that the lag caused by the stretching of pulses is always larger than that caused by the shifting of peaks. According to the definition of the pulse peak lag and the relation between the peak time and energy, one has $t_{p13} = t_{p12} + t_{p23}$. Along with the relationship between the peak lag and CCF lag, the relation $l_{ag13} = l_{ag12} + l_{ag23}$ found by Hakkila and Giblin (2006) can be explained.

According to Ryde and Petrosian (2002), the simplest scenario accounting for the observed GRB pulses is to assume an impulsive heating of the leptons and a subsequent cooling and emission. In this scenario, the rising phase of the pulse, which is referred to as the dynamic time (the crossing time), arises from the energizing of the shell, while the decay phase is due to geometric and relativistic effects in an outflow with a Lorentz factor of $\Gamma \gtrsim 100$. An intuitive speculation is that the dependence of the pulse rise time on energy can be attributed to hydrodynamic processes. In the internal shock model of GRB pulses, there are three contributors to the pulse temporal structure: cooling, hydrodynamics, and angular spreading timescales (Piran 1999, 2005; Mészáros 2002, 2006; Zhang & Mészáros 2004). Thus, the resulting time profile is a convolution of the three processes. Based on the current model which requires a much stronger magnetic field and thus leads to very fast cooling, the typical cooling timescale ($\sim 10^{-6}$ s, see Wu & Fenimore 2000) is much shorter than the observed pulse delays, and hence the cooling timescale can not dominates the pulse profile. The effect of the angular time arising from kinematics, the so-called curvature effect, on the characteristics of pulses, has been intensively studied (Panaitescu & Kumar 2002; Qin 2002; Ryde & Petrosian 2002; Kocevski et al. 2003; Dermer 2004; Dyks et al. 2005; B. Zhang et al. 2006). It was argued that the curvature effect might be responsible for the spectral lag (Salmonson 2000; Ioka & Nakamura 2001; Shen et al. 2005; Ryde 2005; Lu et al. 2006b). The relationship between the pulse width and energy could also be accounted for by the curvature effect (Qin et al. 2004, 2005; Peng et al. 2006). However, Shen, Song, and Li (2005) found that the curvature causes an energy-dependent pulse width distribution but the energy dependence of the width they obtained was much weaker than the observed $W \propto E^{-0.4}$ one. Yi et al. (2006) also found that the curvature effect alone could not explain the difference of the spectral lags (see also Shen et al. 2005; Lu et al. 2006b). Daigne and Mochkovitch (1998, 2003) developed a model in the framework of internal shock model (Rees & Mészáros 1994) and found that if GRB pulses were produced by internal shocks, their temporal and spectral properties were probably governed by the hydrodynamics of the flow rather by the geometry of the emitting shells. Recently, Lu et al. (2007) tentatively analyzed the origination of GRB pulses, and found that the decay phase of the observed pulse originates from the contributions of both the curvature effect and the width of the intrinsic pulse, and the rising phase of the observed pulses only comes from the width of the intrinsic pulse (here the width of the intrinsic pulse is referred to as the dynamic time). We argue that all of the energy-dependent
pulse temporal properties discussed above might probably come from the joint contribution of both the hydrodynamic processes of the outflows and the curvature effect, where the energy-dependent spectral lag may be mainly dominated by the dynamic process and the energy-dependent pulse width may be mainly determined by the curvature effect.

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