BROADBAND LIGHT CURVE CHARACTERISTICS OF GRBs 980425 AND 060218 AND COMPARISON WITH LONG-LAG, WIDE-PULSE GRBS

FU-WEN ZHANG\textsuperscript{1,2,3}

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ABSTRACT

It has been recently argued that low-luminosity gamma-ray bursts (LL-GRBs) are likely a unique GRB population. Here, we present systematic analysis of the light-curve characteristics from X-ray to gamma-ray energy bands for the two prototypical LL-GRBs, 980425 and 060218. It is found that both the pulse width (\(w\)) and the ratio of the rising width to the decaying width (\(r/d\)) of theses two bursts are energy-dependent over a broad energy band. There exists a significant trend that the pulses tend to be narrower and more symmetrical at higher energy bands for the two events. Both the X-rays and the gamma-rays follow the same \(w-E\) and \(r/d-E\) relations. These facts may indicate that the X-ray emission tracks the gamma-ray emission, and both are likely to originate from the same physical mechanism. Their light curves show significant spectral lags. We calculate the three types of lags with the pulse peaking time (\(t_{\text{peak}}\)), the pulse centroid time (\(t_{\text{cen}}\)), and the cross-correlation function (CCF). The derived \(t_{\text{peak}}\) and \(t_{\text{cen}}\) are power-law functions of energy. The lag calculated by CCF is strongly correlated with that derived from \(t_{\text{peak}}\). However, the lag derived from \(t_{\text{cen}}\) correlates less with that derived from \(t_{\text{peak}}\) and CCF. The energy dependence of the lags is shallower at higher energy bands. These characteristics are consistent with that observed in typical long-lag, wide-pulse GRBs, suggesting that GRBs 980425 and 060218 may share a similar radiation physics with them.

Subject headings: gamma rays: bursts — methods: statistical — X-rays: individual (GRB 980425, GRB 060218)

Online material: color figures

1. INTRODUCTION

Two nearby gamma-ray bursts (GRBs), 980425 and 060218, have been detected respectively at the redshifts 0.0085 (Tinney et al. 1998) and 0.0331 (Masetti et al. 2007) at 17:50:29.4 and 19:06:13.9 UT, respectively. The isotropic luminosities \(L_{\text{iso}}\) of GRBs 980425 and 060218 are 1.21 \(\times 10^{57}\) erg s\(^{-1}\) (Hakkila et al. 2008) and 1.2 \(\times 10^{57}\) erg s\(^{-1}\) (Liang et al. 2006, hereafter L06), respectively, marking them prominent low-luminosity GRBs (LL-GRBs) with respect to typical GRBs \(L_{\text{iso}} \sim 10^{50} - 10^{52}\) erg s\(^{-1}\). Both of them are associated with observed supernovae Ic, i.e., GRB 980425 with SN 1998bw (Galama et al. 1998) and GRB 060218 with SN 2006aj (Masetti et al. 2006; Campaan et al. 2006; Pian et al. 2006).

The nature of these two bursts is highly uncertain. Based on the high detection rate inferred from these two nearby events, Liang et al. (2007) proposed that these LL-GRBs might form a unique GRB population, characterized by a high local GRB rate, small beaming factor, and low luminosity (see also Le & Dermer 2007; Guetta & Della Valle 2007). However, the spectral properties of the prompt emission for these two events are apparently different. The peak energy \(E_{\text{p}}\) and the energy dependence of the cosmological rest-frame continuum \(v_{\text{CF}}\) spectrum of GRB 060218 is 4.9 \(\pm 0.3\) keV, which is consistent with the \(E_{\text{p}}-E_{\text{iso}}\) correlation (the so-called Amati relation; Amati et al. 2007). This is reasonable if the Amati relation is due to a radiation effect (Liang & Dai 2004). Furthermore, GRB 060218 roughly complies with the luminosity-lag relation \(L-\tau\) relation; Gehrels et al. 2006, L06) derived from typical GRBs (Norris et al. 2000). These facts indicate that GRB 060218 is a typical X-ray flash, a soft version of GRBs (Lamb et al. 2005). However, GRB 980425 is an apparent outlier with respect to the Amati relation and the \(L-\tau\) relation (Sazonov et al. 2004; Amati 2006). Ghisellini et al. (2006) argued that this may be a hard-to-soft spectral evolution effect. These intriguing observations motivate us to make further analysis of the emission properties of these two events. We focus on their light curve characteristics in an attempt to determine whether evidence exists to explain their abnormal luminosities. Their light curves are composed of a smooth, fast-rise exponential-decay (FRED) pulse with significant spectral lag (Sazonov et al. 2004; L06). Using \textit{CGRO}/BATSE, \textit{BeppoSAX}, and \textit{Swift} observations, we obtain their broadband prompt emissions from X-rays to gamma-rays, which are presented in § 2. We derive the spectral lag (\(\tau\)), the energy dependence of the pulse width (\(w\)), and the ratio of pulse rise to decay (\(r/d\)) for these two events in § 3. Norris et al. (2005, hereafter N05) identified a subgroup of GRBs with a long-lag, wide pulse in their prompt emission profiles. To further examine whether they share some of the properties of typical long-lag, wide-pulse GRBs (LLWP-GRBs), we also make a comparison of the temporal properties of the two bursts with those of the LLWP-GRBs in § 4. Conclusions and discussions are presented in § 5.

2. DATA

GRB 980425 was detected on 1998 April 25.90915 UT with one of the Wide Field Cameras (WFCs) and the Gamma Ray Burst Monitor (GRBM) on board \textit{BeppoSAX}. This burst was also observed with the BATSE instrument on board the \textit{Compton Gamma Ray Observatory (CGRO)} at 21:49:08.7 UT (trigger 6707). The X-ray light curves with a temporal resolution of 1 s in energy bands 2–5, 5–10, and 10–26 keV observed with WFC are available at ASI Science Data Center\(^4\) (Vetere et al. 2007). The

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\textsuperscript{1} National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, P.O. Box 110, Kunming, Yunnan 650011, China; fwzhang@ynao.ac.cn.

\textsuperscript{2} Department of Mathematics and Physics, Guilin University of Technology, Guilin, Guangxi 541004, China.

\textsuperscript{3} The Graduate School of the Chinese Academy of Sciences, P.O. Box 3908, Beijing 100039, China.

\textsuperscript{4} See http://www.asdc.asi.it.
gamma-ray light curves observed with CGRO/BATSE can be obtained via anonymous ftp from the CGRO/BATSE website.\footnote{See ftp://legacy.gsfc.nasa.gov/compton/data/batse/ascii_data/64ms/.
} They are available in four energy bands, 25–50, 50–100, 100–300, and >300 keV, with a temporal resolution of 64 ms. The backgrounds of these light curves are fitted by a polynomial expression, and they were obtained from the CGRO Science Support Center (CGROSSC) at NASA Goddard Space Flight Center through its public archives.\footnote{See http://cossc.gsfc.nasa.gov/docs/cgro/batse/batseburst/sixtyfour_ms/bckgd_fits.html.} Figure 1 shows the background-subtracted light curves in the X-ray and gamma-ray bands (note that the signal in the >300 keV band is not detected, so the light curve in this band is not displayed). All the light curves are shown with respect to the BATSE trigger time, without considering the propagation delay between the spacecraft.

GRB 060218 was detected with the Swift Burst Alert Telescope (BAT) on 2006 February 18.149 UT. Its duration was $T_{90}/C_{24}$ 2000 s in the 15–150 keV energy band. Swift slewed autonomously to the burst, and the X-ray telescope (XRT) and the UV/Optical Telescope (UVOT) started collecting data 159 s after the burst trigger. The early X-ray emission contains a thermal emission component (Campana et al. 2006). L06 derived the X-ray light curves of the nonthermal emission in energy bands 0.3–2, 2–5, and 5–10 keV by subtracting the thermal emission component from the XRT data. The BAT trigger of this event is an image trigger. L06 extracted the gamma-ray emission light curves in the whole BAT energy band (15–150 keV). In our analysis the light-curve data are taken from L06, and are shown in Figure 2.

The light curves of the two events in the gamma-ray energy bands are a long-lag, long-duration single pulse. N05 made an extensive analysis of a sample of GRBs with a long-lag, wide pulse observed by CGRO/BATSE. In order to make a comparison of the two events with these LLWP-GRBs, we used the data for these bursts from N05.

### 3. Energy Dependence of Light Curve Characteristics

From Figures 1 and 2, we find that there is an obvious trend, the pulses becoming narrower at higher energies, and the pulse peaks shifting to later times at lower energies from the X-ray to gamma-ray energy bands for GRBs 980425 and 060218. We also find that the single-pulse structure of these two bursts apparent at higher energies becomes less obvious at lower energies. The loss of pulse structure at lower energies could be due to part to lower signal-to-noise ratio measurements, or to some sort of faint pulse substructure. While checking whether the dependence in the different energy bands are the same, here we pay attention to how the pulse width and spectral lag depend on energy over a broad energy band.

#### 3.1. Pulse Width and Energy Dependence

Although the single-pulse structure of the two bursts is less obvious at lower energies, we still model their light curves in different energy bands by a single FRED pulse. The pulse profiles of GRBs are found to be self-similar across energy bands (e.g., Norris et al. 1996). Kocevski et al. (2003) developed an empirical expression that can be used to fit the pulses of GRBs well. This function can be written as

$$F(t) = F_m \left( \frac{t + t_0}{t_m + t_0} \right)^r \frac{d}{d + r} + \frac{r}{d + r} \left( \frac{t + t_0}{t_m + t_0} \right)^{r+1}$$

where $t_m$ is the time of the maximum flux ($F_m$) of the pulse, $t_0$ is the offset time, and $r$ and $d$ are the rising and decaying power-law

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**Fig. 1.** BeppoSAX and BATSE light curves of GRB 980425. The count rates have been normalized to the peak of each light curve. The fitting curves with eq. (1) are plotted. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 2.** XRT and BAT light curves of the nonthermal emission of GRB 060218. The fitting curves with eq. (1) are also plotted. The data are taken from L06. [See the electronic edition of the Journal for a color version of this figure.]

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5 See ftp://legacy.gsfc.nasa.gov/compton/data/batse/ascii_data/64ms/.

6 See http://cossc.gsfc.nasa.gov/docs/cgro/batse/batseburst/sixtyfour_ms/bckgd_fits.html.
indices, respectively. We fit all the light curves of GRB 980425 in the different energy bands with equation (1) and then measure the values of $w$ and $r/d$. The errors of $w$ and $r/d$ are derived from the simulations by assuming a normal distribution of the errors of the fitting parameters. The reported errors are at $1\sigma$ confidence level. The results are listed in Table 1.

From Table 1, we find a significant trend that the pulses tend to be narrower and closer to symmetric at higher energies for GRB 980425. We show $w$ and $r/d$ as functions of $E$ in Figure 3 (left), where $E$ is the geometric mean of the lower and upper boundaries of the corresponding energy band, which is adopted throughout this paper unless otherwise noted. Apparently both $w$ and $r/d$ are correlated with $E$. A best fit yields $w \propto E^{-0.20 \pm 0.04}$ (Fig. 3, top left) and $r/d \propto E^{0.10 \pm 0.01}$ (Fig. 3, bottom left). The detailed results of the correlation analysis are listed in Table 2. It is found that the $r/d$-$E$ relation of GRB 980425 is consistent with that observed in the majority of GRBs (e.g., N05; Peng et al. 2006), but the power-law index of the $w$-$E$ relation for this event is somewhat larger than that ($\sim 0.4$) previously observed in typical GRBs (e.g., Fenimore et al. 1995; Norris et al. 1996; N05).

Both the relations, $w \propto E^{-0.31 \pm 0.03}$ and $r/d$-$E \propto E^{0.10 \pm 0.03}$ for GRB 060218 are also displayed in Figure 3 (right) and listed in Table 2. We find that this burst roughly satisfies the same $w$-$E$ relation observed in typical GRBs, the index of the $w$-$E$ relation is also shallower, similar to that observed in GRB 980425. Note that the distribution of the power-law indices for a typical GRB sample has a large dispersion; the median value is $\sim 0.4$ (see, Jia & Qin 2005; Peng et al. 2006; Zhang et al. 2007, hereafter Z07). Thus, it is possible that there is no universal power-law index of the $w$-$E$ relation. We also find that the energy dependence of $r/d$ for the burst is consistent with that observed in typical GRBs, but the value of $r/d$ in the 15–150 keV band has large errors. These results show that both the X-rays and gamma-rays follow the same $w$-$E$ and $r/d$-$E$ relations for GRBs 980425 and 060218, indicating that the X-ray emission tracks the gamma-ray emission, and thus the two emission are most likely to originate from the same physical mechanism. A similar case is also found in GRB 060124 (Romano et al. 2006; Zhang & Qin 2008).

3.2. Spectral Lag and Energy Dependence

The light curves of GRBs 980425 and 060218 shown in Figures 1 and 2 display significant spectral lags, with the pulse peaks shifting to later time at lower energies, similar to that observed in typical GRBs by several authors (see e.g., Link et al. 1993; Cheng et al. 1995; Norris et al. 1996, 2000; Band 1997; Wu & Fenimore 2000; Hakkila & Giblin 2004, 2006; Chen et al. 2005; Norris & Bonnell 2006; Yi et al. 2006; Zhang et al. 2006a, 2006b; Hakkila et al. 2007). By using the fitting pulse data, we can measure the pulse peak time ($t_{\text{peak}}$) of each energy band. The results are also listed in Table 1. The top left panel of Figure 4 shows the correlation between $t_{\text{peak}}$ and $E$ for GRB 980425. The best fit to the correlation yields $t_{\text{peak}} \propto E^{-0.35 \pm 0.04}$. The same analysis for GRB 060218 ($t_{\text{peak}} \propto E^{-0.25 \pm 0.05}$) performed by L06 is also displayed in the top right panel of Figure 4. The $t_{\text{peak}}$-$E$ relations for these two bursts are listed in Table 2. We find that the indices of the $t_{\text{peak}}$-$E$ relations are different for the two bursts. The pulse peak lags ($\tau_{\text{peak}}$) are defined as the differences between the pulse peak times in different energy bands (e.g., N05; Z07; Hakkila et al. 2008). The values of $\tau_{\text{peak}}$ between any pairs of the six light curves of GRB 980425 can be simply obtained and are listed in Table 3.

It is well known that the pulse centroid time ($t_{\text{cen}}$) can be more easily measured than the pulse peak time, using $t_{\text{cen}} = \int I(t) dt / \int I(t) dt$, where $I(t)$ is the pulse intensity (see Appendix A in N05). In general, $t_{\text{cen}}$ can be directly estimated from the observed light curve data (e.g., Norris 2002; N05). The observed data are discrete, so, we simply replace the integral by a sum, $t_{\text{cen}} = \sum I(t) \Delta t / \sum I(t) \Delta t$, where $\Delta t$ is the time bin of the observed data. Using this equation, we measure $t_{\text{cen}}$ in the different energy bands for GRBs 980425 and 060218. The errors are estimated from simulations by assuming a normal distribution of the errors of the observed data. The results are reported in Table 1 as well. From Table 1, we find that $t_{\text{cen}}$ and $E$ are also correlated. The best fit to the correlation yields $t_{\text{cen}} \propto E^{-0.40 \pm 0.07}$ for GRB 980425 (Fig. 4, bottom left) and $t_{\text{cen}} \propto E^{-0.15 \pm 0.03}$ for GRB 060218 (Fig. 4, bottom right). Meanwhile, the pulse centroid lags ($\tau_{\text{cen}}$) are defined by the differences between the pulse centroid times in different energy bands, which can be calculated between any two energy bands, and are listed in Table 3 as well. In addition, for the purpose of comparison, we also calculate $t_{\text{cen}}$ and pulse centroid lags ($\tau_{\text{cen}}$) from the fitting light curves.

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TABLE 1

| Band (keV) | $t_{\text{peak}}$ (s) | $t_{\text{cen}}$ (s) | $t_{\text{cen}}$ (s) | $r/d$ | $E$ (keV) |
|-----------|----------------------|----------------------|----------------------|-------|-----------|
| GRB 980425 | (1) 2–5............... | 14.24 ± 0.26 | 26.91 ± 1.14 | 27.10 ± 1.32 | 24.71 ± 3.36 | 0.49 ± 0.11 | 3.2 |
|           | (2) 5–10............. | 13.80 ± 0.25 | 23.98 ± 1.93 | 24.05 ± 1.51 | 22.58 ± 2.98 | 0.53 ± 0.14 | 7.1 |
|           | (3) 10–26............ | 11.73 ± 0.29 | 9.79 ± 3.94 | 14.24 ± 1.84 | 13.67 ± 3.51 | 0.61 ± 0.16 | 16.1 |
|           | (4) 25–50............... | 7.10 ± 0.01 | 11.94 ± 0.48 | 12.42 ± 0.18 | 14.64 ± 0.17 | 0.61 ± 0.01 | 35.4 |
|           | (5) 50–100............... | 5.53 ± 0.01 | 8.61 ± 0.32 | 8.98 ± 0.07 | 13.51 ± 0.11 | 0.65 ± 0.01 | 70.7 |
|           | (6) 100–300............... | 3.81 ± 0.01 | 5.29 ± 0.41 | 5.75 ± 0.08 | 11.16 ± 0.14 | 0.74 ± 0.01 | 173.2 |
| GRB 060218 | (1) 0.3–2............... | 1082 ± 13 | 1362 ± 59 | 1687 ± 98 | 2625 ± 125 | 0.43 ± 0.03 | 0.7 |
|           | (2) 2–5............. | 919 ± 7 | 1236 ± 19 | 1399 ± 49 | 1707 ± 40 | 0.58 ± 0.02 | 3.1 |
|           | (3) 5–10............ | 735 ± 9 | 1082 ± 19 | 1142 ± 45 | 1278 ± 45 | 0.59 ± 0.03 | 6.9 |
|           | (4) 15–150............... | 405 ± 25 | 749 ± 129 | 773 ± 164 | 889 ± 244 | 0.54 ± 0.18 | 36.9 |

\* The values of $t_{\text{cen}}$ are estimated based directly on the observed data.

b The values of $t_{\text{peak}}, w, r/d$, and $E$ of GRB 060218 are taken from L06.
results are listed in Tables 1 and 3. We find that the relation between \( t_{\text{cen}} \) and \( E \) is consistent with that between \( t_{\text{cen}} \) and \( \log E \) as reported in Table 2. We also find that the indices associated with the pulse centroid time and energy for the two bursts are different.

In addition, the lags calculated with the cross-correlation function (CCF), \( \tau_{\text{CCF}} \), have been widely adopted by many authors (Band 1997; Norris et al. 2000; Wu & Fenimore 2000; Hakkila & Giblin 2004, 2006; Chen et al. 2005; Norris & Bonnell 2006; Yi et al. 2006, 2008; Zhang et al. 2006a, 2006b; Z07; Peng et al. 2007; Hakkila et al. 2007). In general, \( \tau_{\text{CCF}} \) can be calculated directly from the observed data. However, since the time resolution of the X-ray light curves of GRB 980425 is very low and different from that of the gamma-ray light curves, we cannot directly use the observed data to measure all lags between any pairs of the light curves. Thus, we estimate \( \tau_{\text{CCF}} \) with the normalized light curves derived from the pulse fits for this event. To reduce the uncertainty in the lag measurement, we adopt the same approach as presented by Hakkila & Giblin (2006). Their GRB pulse model (Norris et al. 1996) is a time-asymmetric function, and has more degrees of freedom than a quadratic (Wu & Fenimore 2000) or a cubic (Norris et al. 2000), which can result in a more accurate CCF fit. This model is used to fit the CCF. The reported lags are derived by averaging lags obtained from CCF measurements spanning a range of temporal shifts (typically, six trial measurements are made over a broad range of CCF values in the vicinity of the CCF peak). The errors in the lags are evaluated by the simulations. The results are also reported in Table 3. The CCF lags of GRB 060218 derived by L06 are available and are reported in Table 3 as well.

![Figure 3](image)

**Fig. 3.**—Dependence of the pulse width (top) and pulse rise-to-decay ratio (bottom) on energy in GRBs 980425 and 060218. The solid lines in the plots are the best fits.

**TABLE 2**

| Parameter | GRB 980425 | GRB 060218 |
|-----------|------------|------------|
| \( \log w \) | \((1.47 \pm 0.06) - (0.20 \pm 0.04) \log E\) | \((3.38 \pm 0.02) - (0.31 \pm 0.03) \log E\) |
| \( \log r/d \) | \((-0.35 \pm 0.01) + (0.10 \pm 0.01) \log E\) | \((-0.32 \pm 0.03) + (0.10 \pm 0.03) \log E\) |
| \( \log f_{\text{peak}} \) | \((1.41 \pm 0.07) - (0.35 \pm 0.04) \log E\) | \((3.04 \pm 0.04) - (0.25 \pm 0.05) \log E\) |
| \( \log t_{\text{cen}} \) | \((1.63 \pm 0.10) - (0.40 \pm 0.07) \log E\) | \((3.14 \pm 0.03) - (0.15 \pm 0.03) \log E\) |
| \( \log t_{\text{cen}} \) | \((1.66 \pm 0.04) - (0.39 \pm 0.03) \log E\) | \((3.22 \pm 0.02) - (0.20 \pm 0.02) \log E\) |
| \( r_{\text{cen}} \) | \((2.18 \pm 2.09) + (1.48 \pm 0.33) r_{\text{peak}}\) | \((47 \pm 62) + (1.23 \pm 0.15) r_{\text{peak}}\) |
| \( \tau_{\text{cen}} \) | \((2.74 \pm 2.23) + (1.59 \pm 0.40) \tau_{\text{CCF}}\) | \((197 \pm 79) + (1.25 \pm 0.27) \tau_{\text{CCF}}\) |
| \( \tau_{\text{CCF}} \) | \((0.11 \pm 0.12) + (0.86 \pm 0.04) r_{\text{peak}}\) | \((-100 \pm 17) + (0.91 \pm 0.08) r_{\text{peak}}\) |
Then the question immediately arises of whether the values of $\tau_{\text{CCF}}$ derived from the fitting curves are convincing? To address this question, we compare the lags calculated from the fitting curves with those derived from the observed data. Using the observed data and the same CCF method, we calculate the lags ($\tau_{\text{CCF}}$) of GRBs 980425 and 060218 in only the X-ray or gamma-ray energy bands. The errors of $\tau_{\text{CCF}}$ are evaluated by the simulations. The results are also reported in Table 3. From Table 3, we find that the calculated lags from the two methods are consistent, but the values of $\tau_{\text{CCF}}$ estimated from the observed X-ray light curves for GRB 980425 have large errors. Thus, our estimated lags from the fitting curves are convincing.

Based on the above results, we can analyze the relationships between the three types of lags. For the purpose of unified comparison, we use all the quantities derived from the fitting light curves. The plots of $\tau_{\text{cen}}$ vs. $\tau_{\text{peak}}$, $\tau_{\text{cen}}$ vs. $\tau_{\text{CCF}}$, and $\tau_{\text{CCF}}$ vs. $\tau_{\text{peak}}$ are displayed in Figure 5. The results of the correlation analysis for the three quantities are listed in Table 2. We find that $\tau_{\text{CCF}}$ and $\tau_{\text{peak}}$ are highly correlated for the multiwavelength observations in GRBs 980425 and 060218, while the other pairs of the quantities are less well correlated. In addition, we find that $\tau_{\text{cen}}$ is systematically larger than both $\tau_{\text{peak}}$ and $\tau_{\text{CCF}}$. These results are consistent with those derived in typical LLWP-GRBs (Z07). As suggested by Z07, $\tau_{\text{CCF}}$ is mainly caused by a shifting of the pulse peaks, while $\tau_{\text{cen}}$ is not. We suspect that $\tau_{\text{CCF}}$ and $\tau_{\text{cen}}$ reflect different aspects of pulse evolution, with one representing the shifting of the pulse peaks and the other describing an enhancement of the pulse timescales. Under this interpretation, the lag caused by the stretching of pulses is always larger than that caused by the shifting of the pulse peaks. In addition, the nonlinear fluctuations statistically present between the different types of lag measurements (e.g., Fig. 5) might be due to the process of pulse evolution and/or to instrumental response. In other words, each type of lag measurement may well be sensitive to different variations pertaining to pulse evolution; these variations may depend on pulse shape, energy, and/or signal-to-noise ratio. It is possible that the different types of lag measurements could be used as a tool for probing aspects of pulse evolution. Thus, we propose that to reveal the evolution of a pulse in detail, both the pulse peak lag and the centroid lag should be measured.

Recently, Lu et al. (2006) considered the contributions of the curvature effect of fireballs to the spectral lag (see also Shen et al. 2005), and tentatively studied the dependence of spectral lag on energy. They considered a wide energy band, ranging from 0.2 to 8000 keV, and then divided the band into 14 geometrical uniform energy bands: $0.2 < E < 0.4$, $0.5 < E < 1$, $1 < E < 2$, $2 < E < 4$, $5 < E < 10$, $10 < E < 20$, $20 < E < 40$, $50 < E < 100$, $100 < E < 200$, $200 < E < 400$, $500 < E < 1000$, $1000 < E < 2000$, $2000 < E < 4000$, and $4000 < E < 8000$ keV. Subsequently, they measured the spectral lags between the first energy band (0.2–0.4 keV) and any of the other bands, and pointed out that the lags increases with energy following a scaling law $\tau \propto E$, and then saturates at a certain energy (see the left panel of Fig. 13 in Lu et al. 2006). Motivated

**Fig. 4.**—Plots of the pulse peak time vs. energy (top) and the centroid time vs. energy (bottom) in GRBs 980425 and 060218. The $\tau_{\text{cen}}$ are estimated directly based on the observed data. The solid lines represent the best fits.

Note that the spectral lag of the Lu et al. (2006) paper was defined as the time between the peaks of the light curves in two different energy bands, which is the pulse peak lag in this paper.
TABLE 3
MULTIBAND SPECTRAL LAGS OF GRBS 980425 AND 060218

| Bands | $\tau_{\text{peak}}$ (s) | $\tau_{\text{cen}}^a$ (s) | $\tau_{\text{cen}}$ (s) | $\tau_{\text{CCF}}$ (s) | $\tau_{\text{CCF}}^a$ (s) |
|-------|----------------|----------------|----------------|----------------|----------------|
| GRB 980425 |
| (1)-(2) | 0.44 ± 0.36 | 2.93 ± 2.24 | 3.05 ± 2.01 | 0.22 ± 0.19 | 0.45 ± 1.56 |
| (1)-(3) | 2.51 ± 0.39 | 17.12 ± 4.10 | 12.86 ± 2.26 | 1.75 ± 0.26 | 1.87 ± 1.69 |
| (1)-(4) | 7.14 ± 0.26 | 14.97 ± 1.23 | 14.68 ± 1.33 | 5.43 ± 0.54 | 5.43 ± 0.54 |
| (1)-(5) | 8.71 ± 0.26 | 18.30 ± 1.18 | 18.12 ± 1.32 | 7.04 ± 0.74 | 7.04 ± 0.74 |
| (1)-(6) | 10.43 ± 0.26 | 21.62 ± 1.21 | 21.35 ± 1.32 | 8.93 ± 0.55 | 8.93 ± 0.55 |
| (2)-(3) | 2.07 ± 0.38 | 14.19 ± 4.39 | 9.81 ± 2.38 | 1.98 ± 0.13 | 1.45 ± 1.15 |
| (2)-(4) | 6.70 ± 0.25 | 12.04 ± 1.99 | 11.63 ± 1.52 | 5.79 ± 0.57 | 5.79 ± 0.57 |
| (2)-(5) | 8.27 ± 0.25 | 15.37 ± 1.96 | 15.07 ± 1.51 | 7.40 ± 0.71 | 7.40 ± 0.71 |
| (2)-(6) | 9.99 ± 0.25 | 18.69 ± 1.97 | 18.30 ± 1.51 | 9.27 ± 0.88 | 9.27 ± 0.88 |
| (3)-(4) | 4.63 ± 0.29 | –2.15 ± 3.97 | 1.82 ± 1.85 | 4.01 ± 0.41 | 4.01 ± 0.41 |
| (3)-(5) | 6.20 ± 0.29 | 1.18 ± 3.95 | 5.26 ± 1.84 | 5.59 ± 0.43 | 5.59 ± 0.43 |
| (3)-(6) | 7.92 ± 0.29 | 4.50 ± 3.96 | 8.49 ± 1.84 | 7.45 ± 0.72 | 7.45 ± 0.72 |
| (4)-(5) | 1.57 ± 0.01 | 3.33 ± 0.58 | 3.44 ± 1.19 | 1.42 ± 0.15 | 1.42 ± 0.15 |
| (4)-(6) | 3.29 ± 0.01 | 6.65 ± 0.63 | 6.67 ± 0.20 | 3.11 ± 0.28 | 3.11 ± 0.28 |
| (5)-(6) | 1.72 ± 0.01 | 3.32 ± 0.52 | 3.23 ± 0.11 | 1.65 ± 0.12 | 1.65 ± 0.12 |

GRB 060218

| Bands | $\tau_{\text{peak}}$ (s) | $\tau_{\text{cen}}^a$ (s) | $\tau_{\text{cen}}$ (s) | $\tau_{\text{CCF}}$ (s) | $\tau_{\text{CCF}}^a$ (s) |
|-------|----------------|----------------|----------------|----------------|----------------|
| (1)-(2) | 163 ± 15 | 126 ± 62 | 288 ± 109 | 43 ± 8 | 39 ± 15 |
| (1)-(3) | 347 ± 16 | 280 ± 62 | 545 ± 108 | 173 ± 25 | 183 ± 37 |
| (1)-(4) | 677 ± 28 | 613 ± 141 | 914 ± 191 | 518 ± 70 | 518 ± 70 |
| (1)-(5) | 184 ± 11 | 154 ± 27 | 257 ± 66 | 81 ± 12 | 71 ± 12 |
| (1)-(6) | 514 ± 26 | 487 ± 130 | 626 ± 171 | 389 ± 47 | 389 ± 47 |
| (3)-(4) | 330 ± 26 | 333 ± 130 | 369 ± 170 | 249 ± 37 | 249 ± 37 |

\( a \) The values of \( \tau_{\text{cen}}^a \) and \( \tau_{\text{CCF}}^a \) are calculated directly based on the observed data.

\( b \) The values of \( \tau_{\text{peak}} \) and \( \tau_{\text{CCF}} \) of GRB 060218 are taken from L06.

![Fig. 5.—Relationships between the three types of lags (\( \tau_{\text{cen}}, \tau_{\text{peak}}, \text{and} \tau_{\text{CCF}} \)). The solid lines are the regression lines, where the correlation coefficients (from top to bottom) are 0.78, 0.74, and 0.99 for GRB 980425, and 0.97, 0.92, and 0.99 for GRB 060218, respectively.](image)
by this, we also investigate the dependence of the three types of lags on energy for GRBs 980425 and 060218. We analyze the lags between the lowest energy band (2–5 keV for GRB 980425 and 0.3–2 keV for GRB 060218) and any of the other high-energy bands; $E$ is the energy of the corresponding high-energy band. The circles, squares, and triangles represent the lags derived from the pulse peak time, centroid time, and CCF, respectively.

Figure 6 shows the relationship between $\tau$ and $E$ (here $E$ denotes the energy of the corresponding high-energy band). We find from Figure 6 that the three types of lags relative to the same low-energy band increase with the energy of the corresponding high-energy band, but their increases become shallow at higher energies. The trend of the $\tau$–$E$ relation for the two bursts seems to be similar to that obtained by Lu et al. (2006). Probably, the curvature effect of the fireballs plays a role in producing the relation (see, e.g., Qin et al. 2004, 2005), but the specifics are currently unclear.

4. COMPARISON WITH TYPICAL LONG-LAG, WIDE-PULSE GRBs

N05 analyzed the temporal and spectral behavior of the wide pulses in 24 long-lag BATSE bursts and suggested that these events may form a separate subclass of GRBs. Although GRBs 980425 and 060218 are two very peculiar low-luminosity events, both of them have a simple temporal structure, and their light curves are composed of a long-duration single pulse with a long spectral lag. It would be very interesting to see whether they have the different temporal properties of typical LLWP-GRBs to explain their abnormal luminosities. In order to clarify this issue, we first compare the distribution of $(w, \tau)$ of the two bursts with that of the bursts in the N05 sample. Apart from GRB 060218, the values of $w$ for the other bursts are directly taken from Table 2 of N05. The definition of $w$ given by N05 is the width between

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Fig. 6.—Plots of $\tau$ vs. $E$, where $\tau$ are spectral lags between the first energy band (2–5 keV for GRB 980425 and 0.3–2 keV for GRB 060218) and any of the other high-energy bands; $E$ is the energy of the corresponding high-energy band. The circles, squares, and triangles represent the lags derived from the pulse peak time, centroid time, and CCF, respectively.

Fig. 7.—Relation between pulse spectral lags and pulse widths, where $\tau_{\text{peak,B3}}$, $\tau_{\text{cen,B3}}$, and $\tau_{\text{CCF,B3}}$ are the pulse peak lags, centroid lags, and CCF lags in the 100–300 keV (B3) and 25–50 keV (B1) bands, and $w_{B1}$ and $w_{B3}$ are the pulse width measured between the two 1/e intensity points defined by N05 in the B1 and B3 bands, respectively. The solid line is the best fit ($\tau_{\text{cen,B3}} = 0.089 w_{B3}^{0.32}$) obtained by N05. The filled diamonds represent GRB 980425 and GRB 060218, and the open circles are the other bursts in the N05 sample besides GRB 980425.

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9 GRB 980425 is included in the N05 sample.
the two 1/e peak intensity points of the pulse; we also measure the pulse width of GRB 060218 in the different energy bands according to this definition. We obtain \( w = 1053 \pm 275, 1574 \pm 68, 2107 \pm 73, \) and \( 3668 \pm 214 \) s in the energy bands 15–150, 5–10, 2–5, and 0.3–2 keV, respectively. In general, the spectral lags (\( \tau_{B1} \)) of the BATSE bursts between energy bands 100–300 keV (B3) and 25–50 keV (B1) have been well estimated and widely adopted by many authors. We only analyze the spectral lags in the two energy bands.\(^{10}\) The values of \( \tau_{\text{peak,B31}} (177 \pm 16 \text{ s}) \) and \( \tau_{\text{CCF,B31}} (61 \pm 26 \text{ s}) \) of GRB 060218 estimated by L06 are available. Using the same extrapolated method as L06, we obtain \( \tau_{\text{cen,B31}} = 219 \pm 30 \text{ s}, w_{B1} = 1065 \pm 61 \text{ s}, \) and \( w_{B3} = 585 \pm 34 \text{ s} \) for GRB 060218. Figure 7 shows the relationships of \( \tau_{\text{cen,B31}}, \tau_{\text{CCF,B31}}, \) and \( \tau_{\text{cen,B31}} \) against \( w_{B1} \) and \( w_{B3} \) for the N05 sample as well as GRB 060218. We find from Figure 7 that the distribution of \( (w, \tau) \) of GRB 980425 is completely consistent with that of the other LLWP-GRBs (as pulse width increase, the spectral lag tends to increase; see N05), and GRB 060218 also fall into the same sequence, although it has the longest pulse width and spectral lag observed to date.

Recently, Peng et al. (2007) suggested that the correlation between pulse spectral lag and pulse width might be caused by the Lorentz factor of the GRBs. However, the pulse relative spectral lag (RSL), which is defined as the ratio of the pulse spectral lag between light curves observed in two different energy bands (usually the BATSE B1 and B3 bands are adopted) to the pulse width (see Zhang et al. 2006a, 2006b; Peng et al. 2007; Zhang & Xie 2007) is a unique and intrinsic quantity, since such a definition can reduce both Doppler and cosmological time dilation effects on the observations, owing to \( \tau \propto \Gamma^{-2} (1 + z) \) and \( w \propto \Gamma^{-2} (1 + z) \) (Zhang et al. 2006b; Norris et al. 2000; Kocevsk & Liang 2006; Peng et al. 2007; Zhang & Xie 2007). Therefore, we also analyze the relation between the pulse RSLs and pulse widths for the typical LLWP-GRBs, as well as GRBs 980425 and 060218. The results are plotted in Figure 8. We find from Figure 8 that the pulse RSLs are not correlated with the pulse widths, and the pulse RSLs of GRBs 980425 and 060218 are fully consistent with those of the other LLWP-GRBs.

In addition, we also compare the two bursts with the events of the N05 sample for \( r/d \) vs. \( w \). Using the data of Table 2 and equation (5) in N05, we derive the values of \( r/d \) in the B1 and B3 energy bands for all the bursts in the N05 sample. Figure 9 shows the plots of \( r/d \) vs. \( w \) in the B1 and B3 energy bands.\(^{11}\) As can be seen from Figure 9, the pulse rise-to-decay ratios of GRBs 980425 and 060218 are in good agreement with those of the other LLWP-GRBs. These results indicate that GRBs 980425 and 060218 may share a similar radiation physics with them.

5. CONCLUSIONS AND DISCUSSION

We have analyzed the prompt light curve characteristics of GRBs 980425 and 060218 from X-ray to gamma-ray energy bands.

\(^{10}\) The data are taken from Z07 for the N05 sample.

\(^{11}\) The values of \( r/d \) for GRB 060218 have large errors at higher energies, which cannot be estimated well, so we take the value in the 15–150 keV (0.56 ± 0.15) as that in the B1 and B3 energy bands, which cannot affect the results more.
We find that both the pulse width $w$ and the ratio of pulse rise-to-decay $r/d$ are energy-dependent for these two bursts over a broad energy band. There exists a significant trend that the pulses of these two bursts tend to be narrower and more symmetric at higher energy bands. Both the X-rays and gamma-rays of the two events follow the same $w$-$E$ and $r/d$-$E$ relations, but the power-law indices of the $w$-$E$ relations are somewhat larger than those observed previously in typical GRBs (Fenimore et al. 1995; Norris et al. 1996; N05; Peng et al. 2006).

The light curves of GRBs 980425 and 060218 show significant spectral lags, with the pulse peaks shifting to later time at lower energies. We calculate the three types of lags, $\tau_{\text{peak}}$, $\tau_{\text{cen}}$, and $\tau_{\text{CCF}}$, with the pulse peaking time ($t_{\text{peak}}$), the pulse centroid time ($t_{\text{cen}}$), and the cross-correlation function (CCF). The derived $t_{\text{peak}}$ and $t_{\text{cen}}$ are a power-law function of energy, and $\tau_{\text{CCF}}$ is strongly correlated with $\tau_{\text{peak}}$, but the other pairs of the quantities are less well correlated. Our analysis also show that $\tau_{\text{cen}}$ is systematically larger than both $\tau_{\text{peak}}$ and $\tau_{\text{CCF}}$. The relationships between the three types of lags and energy are investigated as well. We find that the lags relative to the same low-energy band increase with the energy of the corresponding high-energy band, but their increases becomes shallow at higher energies.

Although GRBs 980425 and 060218 are two very peculiar low-luminosity events, the temporal and spectral characteristics of these two bursts are normal when compared to other typical LLWP-GRBs.

Our analysis is performed in the observer frame, rather than in the GRB rest frame. This makes the comparison slightly inappropriate, since GRBs 980425 and 060218 are low-redshift bursts, but the normal long-lag GRBs have been observed at larger redshifts (typically $z \sim 1$). Recently, Hakkila et al. (2008) found that the rest-frame pulse duration ($w_0$), pulse peak lag ($\tau_0$), and isotropic pulse peak luminosity ($L$) are highly correlated for the pulses of BATSE GRBs with known redshifts. Remarkably, the
underluminous GRB 980425 follows the $w_0$-$\tau_0$ relation well, but deviates from the $L$-$\tau_0$ relation. Meanwhile, we also analyze the distribution of GRB 060218 in both $w_0$-$\tau_0$ and $L$-$\tau_0$ in Figure 10. From this figure, we find that GRB 060218 also complies with the $w_0$-$\tau_0$ relation well, and is inconsistent with the $L$-$\tau_0$ correlation. This result further reinforces our conclusion that the temporal and spectral characteristics of GRBs 980425 and 060218 are normal. In addition to the time dilation effect on the rest-frame lags and durations [the correction is $(1+z)^{-1}$], the energy correction ($K$ correction) also affected the two rest-frame quantities, since the normal pulses are subsequently observed at lower energies than low-luminosity pulses, and both the lags and durations are energy-dependent ($\tau \propto E^{-0.4}$ and $\nu \propto E^{-0.4}$; see, e.g., Norris et al. 1996; N05; Z07). The energy correction to the rest frame for the lags and durations is approximately $(1+z)^{0.33}$ (e.g., Gehrels et al. 2006). This effect is not considered here. When comparing these observations to observer-frame observations of higher $z$ bursts, both the energy correction and time dilation correction should be taken into account.

Stern et al. (1999) first suggested that there is a group of simple bursts with peak fluxes near the BATSE trigger threshold; the average profiles of dim bursts were less complex than those of bright bursts. Norris (2002) found that the proportion of long-lag bursts within long-duration bursts increases from negligible among bright BATSE bursts to $\sim$50% at the trigger threshold. N05 proposed that these long-lag bursts may be underluminous and form a separate subclass of GRBs (see also Liang et al. 2007; Le & Dermer 2007; Guetta & Della Valle 2007; Ghisellini et al. 2007; Daigne & Mochkovitch 2007; Foley et al. 2008). However, the Hakkila et al. (2008) results challenge this statement. They found that $L$, $\tau_0$, and $w_0$ are correlated intrinsic properties of most GRB pulses. GRBs 980425 and 060218 are fully consistent with the $w_0$-$\tau_0$ relation holding for the normal GRB pulses. Given this, the evidence for a separate class of LLWP-GRBs seems to be much weaker. However, both of these GRBs are apparent outliers with respect to the $L$-$\tau_0$ relation. This result makes the underluminous features of GRBs 980425 and 060218 that much more unusual. Based on the fact that redshifts of three such bursts are available (GRB 980425, Galama et al. 1998; 031203, Malesani et al. 2004; and 060218, Mirabal & Halpern 2006), some authors have argued that the low-luminosity bursts are probably relatively nearby, and the local event rate of these events should be much higher than expected from the high-luminosity GRBs (Cobb et al. 2006; Pian et al. 2006; Soderberg et al. 2006; Liang et al. 2007; Le & Dermer 2007; Guetta & Della Valle 2007). There are two scenarios that have been proposed to explain their wide-pulse, long-lag, and underluminous features. One possible scenario is that these GRBs are normal events viewed off-axis (e.g., Nakamura 1999; Salmonson 2000; Yamazaki et al. 2003). The second scenario is that these features are intrinsic, and may possibly be due to lower Lorentz factors (Kulkarni et al. 1998; Woosley & MacFadyen 1999; Salmonson 2000; Dai et al. 2006; Wang et al. 2007) or a different type of central engine (e.g., neutron stars rather than black holes; see Mazzali et al. 2006; Soderberg et al. 2006; Toma et al. 2007).

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