Broadband light curve characteristics of two prototypical LL-GRBs, 980425 and 060218

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## Peculiar observed properties of GRBs 980425 and 060218

<table>
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<tr>
<th>Observed properties</th>
<th>Typical long GRBs</th>
<th>GRB 980425</th>
<th>GRB 060218</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{iso}$ (erg)</td>
<td>$\sim 10^{51}-10^{54}$</td>
<td>$\sim 6 \times 10^{47}$</td>
<td>$\sim 7 \times 10^{49}$</td>
</tr>
<tr>
<td>$L_{iso}$ (erg/s)</td>
<td>$\sim 10^{50}-10^{52}$</td>
<td>$1.21 \times 10^{47}$</td>
<td>$1.2 \times 10^{47}$</td>
</tr>
<tr>
<td>$E_p$ (keV)</td>
<td>$\sim 200$</td>
<td>$\sim 55$</td>
<td>$\sim 5$</td>
</tr>
<tr>
<td>$z$</td>
<td>$z_{\text{mean}} \sim 1.8$</td>
<td>0.0085</td>
<td>0.033</td>
</tr>
<tr>
<td>$T_{90}$ (s)</td>
<td>Meadian $\sim 30$</td>
<td>34.88</td>
<td>$\sim 2000$</td>
</tr>
<tr>
<td>$\tau$ (s)</td>
<td>$\sim 0.05$</td>
<td>$\sim 3$</td>
<td>$\sim 61$</td>
</tr>
<tr>
<td>GRB/SN</td>
<td>--</td>
<td>SN 1998bw</td>
<td>SN 2006aj</td>
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<tr>
<td>Time profile</td>
<td>Complicated</td>
<td>Single-pulse</td>
<td>Single-pulse</td>
</tr>
<tr>
<td>$E_{iso}$-$E_p$ relation</td>
<td>Satisfy</td>
<td>Deviate</td>
<td>Satisfy</td>
</tr>
<tr>
<td>$L_{iso}$-$\tau$ relation</td>
<td>Satisfy</td>
<td>Deviate</td>
<td>Roughly satisfy</td>
</tr>
</tbody>
</table>
• The nature of these two bursts is highly uncertain.

• Based on the high detection rate inferred from these two nearby events, some authors proposed that these LL-GRBs might form a unique GRB population (Liang+07, Le & Dermer 07; Guetta & Della Valle 07, Francisco+09).

• Their intriguing observations motivate us to make further analysis of the emission properties of these two events.

• We mainly focus on their light curve characteristics in an attempt to determine whether evidence exists to explain their abnormal luminosities.
Broadband light curves

GRB 980425

BeppoSAX + BATSE

GRB 060218

Swift-XRT + BAT,
Pulse fit function

\[ F(t) = F_m \left( \frac{t + t_0}{t_m - t_0} \right)^{\alpha} \left[ \frac{\alpha}{\alpha + 1} \right] \left( \frac{t + t_0}{t_m - t_0} \right)^{\alpha + 1} - \frac{\alpha}{\alpha + 1} \frac{1}{t_m - t_0} \left( t + t_0 \right)^{\alpha + 1} \]

Kocevski et al. 2003
Energy dependence of pulse width and ratio of pulse rise-to-decay

$W \propto E^{-0.4}$ (e.g., Fenimore et al. 1995; Norris et al. 1996; 2005)

$W \propto E^{-0.20\pm0.04}$

$r/d \propto E^{-0.10\pm0.01}$

$r/d \propto E^{-0.13\pm0.04}$

Note: 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; 2005; Peng et al. 2006)
Distribution of indices of relation between pulse width and energy

Peng et al. 2006

Zhang et al. 2007
Pulse spectral lag

- **Pulse display significant spectral lag** (the pulse peaks shifting to later time at lower energies)

- **Three types of pulse lags:**
  - **Peak lag** ($\tau_{\text{peak}}$): the differences between the pulse peak times in different energy bands (e.g. Norris+05, Zhang+07, Hakkila+08)
  - **CCF lag** ($\tau_{\text{CCF}}$): calculated with the cross-correlation function (CCF) (e.g. Band+93, Norris+2000, 2005, 2006; Chen+ 2005, Yi+2006)
  - **Centroid lag** ($\tau_{\text{cen}}$): the differences between the pulse centroid times in different energy bands (e.g. Norris+96; 05; Zhang+07)

  where, **Pulse centroid time** $t_{\text{cen}} = \frac{\int I(t)tdt}{\int I(t)dt}$ (Norris+05)

  for discrete observed data $t_{\text{cen}} = \frac{\sum I(t)t\Delta t}{\sum I(t)\Delta t}$
Pulse spectral lag

Relations between the three types of lags

\( (T_{\text{peak}} , T_{\text{cen}} \text{ and } T_{\text{CCF}}) \)

We suspect that CCF lag and centroid lag 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. It is possible that the different types of lag measurements could be used as a tool for probing aspects of pulse evolution.
Norris et al. (2005) 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 to explain their abnormal luminosities.
Compare with typical long-lag, wide pulse GRBs

Pulse spectral lag vs. pulse width

Note: GRB 980425 is completely consistent with that of the other log-lag, wide-pulse GRBs (as pulse width increase, the spectral lag tends to increase; see Norris et al. 2005), and GRB 060218 also fall into the same sequence.
Pulse Relative Spectral Lag (RSL)

- Some authors suggested that the correlation between pulse spectral lag and pulse width might be caused by the Lorentz factor of the GRBs (Zhang+06,08,Peng 07).

- However, the pulse relative spectral lag (RSL), which is defined as the ratio of the pulse spectral lag to the pulse width, which is a unique and intrinsic quantity, since such a definition can reduce both Doppler and cosmological time dilation effects on the observations.
Relative pulse lag vs. pulse width

![Graph showing the relationship between pulse lag and pulse width](image-url)
The pulse rise-to-decay ratios of GRBs 980425 and 060218 are in good agreement with those of the other LLWP-GRBs.
Hakkila et al. (2008) found that pulse peak lag, pulse luminosity, and pulse duration are strongly correlated in the rest frame, implying that most GRB pulses have similar physical mechanisms. Pulses are the basic, central building blocks of GRB prompt emission.
Compare with pulses of BATSE GRBs in the rest frame

![Graphs showing relationships between pulse durations and luminosities for BATSE GRBs.](image)

*Fig. 10.—Left: Rest-frame pulse duration $w_0$ vs. pulse peak lag $\tau_0$ for fits of BATSE GRBs having known redshifts (the data are taken from Hakila et al. 2008), as well as GRB 060218. Right: Isotropic pulse peak luminosity $L$ vs. pulse peak lag $\tau_0$ for the pulses shown in the left panel. The open circles represent the pulses from GRB 971214, GRB 980703, GRB 970508, GRB 990510, GRB 991216, and GRB 990123, and the filled diamonds represent GRB 980425 and GRB 060218. The solid lines are the best fits obtained by Hakila et al. (2008).*
Conclusion

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

• 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 width-energy and ratio of pulse rise-to-decay-energy relations.

• The light curves of GRBs 980425 and 060218 show significant spectral lags, with the pulse peaks shifting to later time at lower energies.

• Although GRBs 980425 and 060218 are two very peculiar low-luminosity events, the light curve characteristics of these two bursts are normal.
Discussion

• Normal temporal properties makes the under-luminous features of GRBs 980425 and 060218 that much more unusual.

• There are two scenarios that have been proposed by some authors to explain their wide-pulse, long-lag, and under-luminous features.

1. These GRBs may be normal events viewed off-axis (e.g., Nakamura 1999; Salmonson 2000; Yamazaki et al. 2003).

2. These features are intrinsic, which may possibly be due to lower Lorentz factors (e.g., Kulkarni et al. 1998, 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)