Properties of X-Ray Afterglows
of Gamma-Ray Bursts

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Outline

Properties of Gamma-ray bursts (GRBs)
- Swift detected 160 GRBs during 2005/01-2006/09.
- Systematic analysis of 160 prompt emissions

Properties of the early X-ray afterglows
- Systematic analysis of 128 X-ray afterglows:
  - Properties of rapid decay, shallow decay, X-ray flares
- Identification of rapid decay phase
- Properties of the X-ray flares
- Relation of the shallow decay phase and prompt emission
Gamma-Ray Bursts

Gamma-ray bursts (GRBs) are
- the most energetic explosions in the universe.
- at the cosmological distances (average redshift: \( z \approx 1.3 \)).
- At least some GRBs are associated with supernova explosions.

Afterglows are
- broad-band (radio/infrared /optical/X-ray).
- Most lightcurves show a smooth power-law decay with the time (\( F \propto t^{-1} \)).

The afterglow spectrum of GRB 030329 reveals the spectral signature of Type-Ib/c supernova.
Radiation mechanism of GRBs

Central engine

Internal shock

External shock

\[ >100 \]

ISM

Kinetic energy

Shock dissipation

Luminosity

GRB

Synchrotron radiation

Afterglow

Time
Afterglow observation

Afterglows provide:
- accurate GRB position
- redshift
- GRB jet structure
- energy balance

What is the connection between the GRB and the afterglow?
Simple power-law function?
Light curves of the early optical afterglows

However,
some optical afterglows show deviations from a smooth power-law.

- **Shallow decay phase** was observed in the early optical light curve.
- **Steep decay** was observed in the early optical light curve.
  ( **Bump** was observed in the late time (1 day~).)
Swift

Swift is the first mission with ability to begin multi-wavelength observations within ~1 min after the detection of GRBs

Launched in 2004/11/20

Slews to the GRB position

BAT (Burst Alert Telescope)
Gamma-ray imager
(15 - 150 keV)

UVOT
UV/optical telescope
(170-600 nm)

XRT
X-ray telescope
(0.3 - 10.0 keV)

Swift makes it possible to perform follow-up observations within 100 s after the bursts.
Swift GRBs
Temporal studies

Light curves in the energy range of 15-150 keV
Burst duration

- Duration are distributed around 10-100 s.
- Swift GRBs do not show clear “bimodal” distribution.

Differences of the energy band and trigger system?
Spectral studies

Systematic analysis of 160 prompt emissions (2005/01-2006/09)

- Typical GRB Band function $\Gamma_1 \sim -1, \Gamma_2 \sim -2.2, E_p \sim 250$ keV
- Best fit models of BAT spectra (15-150 keV)
  - 134 GRBs: single power-law (photon index $\sim -1.5$)
  - 26 GRBs: cutoff power-law
- For six GRBs which obtained both redshift and $E_p$, follow the $E_p \propto E_{\text{iso}}^{0.5}$ and $L_p \propto E_p^{2.0}$ relation.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$E_{\text{peak}}$ (~250 keV)</th>
<th>$E_{\text{iso}}$ ($10^{52}$ erg)</th>
<th>$L_p$ ($10^{52}$ erg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>$E^{-1}$</td>
<td>$E_{\text{iso}} (10^{52}$ erg)</td>
<td>$L_p$ ($10^{52}$ erg/s)</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$E^{-2.2}$</td>
<td>($1+z$) $E_p$ (keV)</td>
<td>$\Gamma_1 \sim -1.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Gamma_2 \sim -2.2$</td>
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</tbody>
</table>
X-ray afterglows
Light curves of X-ray afterglows show three distinct power-law segments.
- initial steep decay phase ($\beta_1 \sim -3$)
- very shallow decay phase ($\beta_2 \sim -0.5$)
- steeper decay phase ($\beta_3 \sim -1$)
- X-ray flares
Rapid decay
Curvature effect

The prompt emission from the large angles ($\theta > \theta^{-1}$) that reaches observer at late time ($t \sim R^{2}/2c$).

$$F_\theta \sim (t-t_0)^{-\frac{\theta}{\theta}} \theta^{-\frac{\theta}{\theta}} \sim (t-t_0)^{-2-\frac{\theta}{\theta}} \theta^{-\frac{\theta}{\theta}}$$

$$\theta = 2 + \frac{\theta}{\theta}$$  (Kumar & Panaitescu 2000)
\( t_0 = \text{trigger time} \)

The \( \square - \square \) relation is satisfied in most cases, but some cases show a steeper temporal decay index (\( \square > 2+\square \)).

We calculated the \( t_0 \) values by fitting the light curve with the function (Zhang et al. 2006, Liang et al. 2006)

\[
F_\square = A (t - t_0)^{-2+\square} / t_0 + B t^{-C}
\]

\( t_0 \) values correspond to the beginning of the last pulse.
X-ray flares
X-ray flares show large amplitude and short timescale. Temporal decay index before and after the flare is approximately identical.

Afterglow (external shock) variability or not?
Theoretical models of afterglow variability

- Fluctuation in the ambient density
- Patchy shell model
- Refreshed shock model
- Long-acting engine model (Internal shock model)
Kinematical limits on afterglow variability (Ioka et al. 2005)

The X-ray flares with short time scale and large amplitude are difficult to explain with external shock.

Long-acting engine model (Internal shock)
X-ray flare start time

We calculated the $t_0$ values of X-ray flares by assuming the $\Delta t - \Delta E$ relation (Liang et al. 2006).

$t_0$ values are determined near the beginning of the rising segment of X-ray flares.

X-ray flares are due to central engine activity after the prompt emission is over.
Temporal profiles

Temporal profiles of GRB pulses are characterized by Norris et al. (1996).

- **Rise time**
- **Decay time**
- **Pulse FWHM**
- **Sharpness**

Pulse width $t \sim R/2c$ (sharpness $\sim 1-2$)

Small Lorentz factor of the shell or/and large emission radius
Spectral studies

We studied the spectral properties of individual X-ray flares using the XRT data (0.5-10 keV).

Best fit model: power-law ($\Gamma \propto E^{-\Gamma}$)

- **Photon index $\Gamma > 2.0$**
  Spectral Peak energy is below the XRT energy band.
  $E_p < 0.5$ keV

- **Photon index $\Gamma < 2.0$**
  Spectral Peak energy is within or above the XRT energy band.
  $E_p \sim 0.5$-10 keV or $E_p > 10$ keV

We tried to fit the spectra using both the BAT and XRT data.

Distribution of the photon indices
We performed spectral fitting using both BAT and XRT data.

**Best fit model**
- **7 events**: power-law \( f < 2.0 \)
- **3 events**: cutoff power-law or Band function

Spectral peak energies are located above the BAT energy band. \( E_p > 150 \) keV.

\( E_p \) of X-ray flares are distributed 0.5~few hundred keV.
Summary of X-ray flares

- X-ray flares with large amplitude and short timescale are difficult to explain with afterglow (external shock) models.
- $T_0$ of most X-ray flares are consistent with being near the beginning of the rising segment.
- Temporal profiles and spectral properties of X-ray flares and GRB have many common characteristics.

X-ray flares are likely due to central engine activity (internal shock scenario), after the GRB is over.
Shallow decay
We examined if there are any correlation between the parameters of prompt emission and the shallow decay phase?

We compared the $E_{\text{iso}}$ and the end time of the shallow decay phase $T_{b,2}$. 

Theoretical models of shallow decay:
- Continuous energy injection model
- Inhomogeneous jet model
- Time-dependent microphysics model
Estimation of the $E_p$

Isotropic luminosity is estimated as:

$$L_{iso} = 4 \gamma d_L^2 F_0 \left( \frac{1}{2-\gamma} \right) \left( 1/(2-2.2) \right) E_p$$

$L_{iso} - E_p$ relation is given by Ghirlanda et al. (2005):

$$E_p / 100 \text{ keV} = 4.88 \left( L_{iso} / 1.9 \gamma 10^{52} \text{ erg/s} \right)^{0.5}$$

We can obtain the $E_p$. 

BAT spectra are described by a PL. BAT cannot well determine $E_p$ and high energy photon index.
Correlation between $E_{\text{iso}}$ and $T_{b,2}$

The larger the isotropic GRB energy ($E_{\text{iso}}$), the earlier the end time of shallow decay phase.
Energy injection

- Refreshed shock
  - The inner shell finishes to catch up with the outer shell at $T_{b,2}$.

- Long-lived central engine
  - X-ray flares require episodic energy injection.
  - However,
  - Shallow decay require smooth and continuous energy injection.

- GRB with large $E_{\text{iso}}$ eject shells with large Lorenz factors.
- GRB with large $E_{\text{iso}}$ eject shells more rapidly.
Inhomogeneous jet

When the shell is decelerated to $\sim 1/\nu$, it begins to spread sideway.

Shallow decay phase
Time-dependent microphysics

Energy fraction $\mathcal{B}_B, \mathcal{B}_e$ depends on the shock’s Lorentz factor $\gamma$.

- For $\gamma > \gamma_0$, $\mathcal{B}_e, \mathcal{B}_B$ vary in the early afterglow.
- For $\gamma < \gamma_0$, $\mathcal{B}_e, \mathcal{B}_B$ are constant as observed in the late time afterglow.
  ($\gamma_0$ is the Lorentz factor of the outflow at the X-ray decline transition.)

$T_{b,2}$ corresponds to the time at which the $\gamma$ is decelerated to $\gamma_0$.

$\gamma$ of the external shock evolves as $\gamma(t) \propto E_{iso}^{1/8} t^{-3/8}$

$$T_{b,2} \propto \gamma_0^{8/3} E_{iso}^{1/3}$$

Positive correlation between $T_{b,2}$ and $E_{iso}$.

This relation is inconsistent with the observational result of inverse correlation between $T_{b,2}$ and $E_{iso}$. 
Summary of shallow decay phase

From $E_{\text{iso}} - T_{b,2}$ correlation,

- The shallow decay phase are likely not due to the time-dependent microphysics model.

However,

- Energy injection model and Inhomogeneous jet model have a serious problem.
  Unreasonably high gamma-ray efficiency of GRBs $\sim 75\text{-}90\%$ (Toma et al. 2006, Ioka et al. 2006)
Conclusion

X-ray flares
- X-ray flares are likely due to long central engine activity.
- Temporal profiles and spectral properties of X-ray flares and GRB have many common characteristics.

Shallow decay phase
- The end time of the shallow decay phase is anti-correlated with $E_{\text{iso}}$.
- The shallow decay phase are likely not due to the time-dependent microphysics model.
  However, other models (energy injection model and inhomogeneous jet model) have a serious problem.