Extended X-ray emissions following short gamma-ray bursts (SGRBs) lasting ~100 sec are powerful and thus can be promising electromagnetic counterparts to gravitational waves. To study the characteristics of the extended emission and even the progenitor of SGRBs, we investigate the early X-ray light curves of 26 SGRBs with known redshifts whose data were obtained with the X-Ray Telescope on board the Neil Gehrels Swift Observatory (Swift). From this analysis, we found that almost all of the rapid decline of the early X-ray light curves can be derived an exponential decay model with the time constant of 20 – 200 sec. We also show a strong correlation between the maximum luminosity expected from the model and the time constant with a power-law index of ~ 3.3 whose chance probability is 8.2 x 10^{-3} if there is no observation bias of Swift. The exponential temporal decay may be represented by the spin-down timescale of the rotation energy of a highly magnetized neutron star, and/or fallback accretion onto a disk surrounding a black hole with an exponentially decaying magnetic flux by magnetic reconnection. arXiv:1904.10775!

1. Introduction

**Short Gamma-Ray Burst (SGRB)**
- Sub-class of GRBs with $T_{90} < 2$ sec
- Thought to originate from mergers of compact star binary, such as double neutron stars → coincide with GW
- Collimated and beamed ($\theta \sim 1/\Gamma \sim 0.01$) promising counterpart to GW

**Extended X-ray Emission**
- (temporally) Sub-class of SGRBs lasting about 100 sec
- comparable energy with that of Prompt (in 15-150 keV)
- rather wide ($\theta > 10^{°}$, Bucciantini+ 2011)

**Purpose**
Study the property and even physical origin of the extended emission by analyzing the temporal behavior of its light curve for future GW observation

2. Date Analysis

**Event Selection (until the end of 2018 August)**
1. SGRBs ($T_{90A}<2$ sec) and SGRB candidates ($T_{90}>2$, but hard spectrum index and/or zero consistent spectral lag) detected by Burst Alert Telescope (BAT) aboard the Neil Gehrels Swift Observatory (Swift) with known redshift
2. Observed by the X-Ray Telescope (XRT) with the observation start time of > 300 sec since the GRB trigger

261 events with known redshift from 141 Swift SGRBs

**Light Curve Fitting**

The light curve of the extended emission was analyzed with exponential decay model (Kagawa+ 2015) and power-law decay model (Kisaka+ 2015, 2017). In particular, the PL model is considered with a black hole engine of a merger remnant whose rotation energy is extracted by a Blandford – Znajek jet (Blandford & Znajek 1977) and ejecta fall back (see also Kisaka & Ioka 2015)

**EXP model:** $L_{	ext{EE}} \propto \exp(-t/\tau_{	ext{EE}}) + L_p(1 + \frac{t}{\tau_{	ext{EE}}})^{1200}$

**PL model:** $L_{	ext{EE}} \propto (1 + \frac{t}{\tau_{	ext{EE}}})^{40/9}$

These models are inferred from Yamazaki 2009, Kagawa+ 2015, Kisaka+ 2015, 2017. In particular, the PL model is considered with a black hole engine of a merger remnant whose rotation energy is extracted by a Blandford – Znajek jet (Blandford & Znajek 1977) and ejecta fall back (see also Kisaka & Ioka 2015)

**Table 1.** Results of model fitting to the X-ray light curve of selected SGRBs, green: EXP model, red: PL model.

From the fitting results, such as $\chi^2$, we find that 23 of the 242 events can be described with the EXP model, except for the GRB 051221.

The EXP model is more suitable to comprehensively describe the extended emission light curve than the PL model

3. Energy Comparison with That of Prompt Emission

**Estimate the Isotropic Energy**

- **Prompt Emission:** Events observed by other detectors whose energy range covers the $t_{\text{peak}}$ of the prompt emission to estimate the energy bolometrically. → 15 events
- **Extended Emission:**
  \[ \int_0^{\infty} L_{\text{EE}} \exp(-t/\tau_{\text{EE}}) dt = L_{\text{EE},\text{iso}} \]

- **Observation bias:** The Swift/XRT detectable extended emissions would have a larger normalization $L_{\text{EE}}$ than the detection limit of the XRT ($t_{\text{start}}$, $t_{\text{end}}$) described as
  \[ L_{\text{XRT}(t_{\text{EE}})} = \frac{4n_{\text{SGRB}}}{10}$

  The extended emissions with $T_{90} < 20$ sec are brighter than $L_{\text{XRT}(t_{\text{EE}})}$ by 0.72 (averaged value) by a factor of $-10$.

**The correlation is intrinsic with no observation bias**

4. Physical Origin

**Exponential decay model of Extended Emissions**

1. **Jet Luminosity:** $L_{\text{EE}} \propto B^2$
   (Blandford & Znajek 1997)

2. **Fallback accretion onto a disk surrounding a black hole with an exponentially decaying magnetic flux by magnetic reconnection.**

   - **Jet Luminosity:** $L_{\text{EE}} \propto B^2$
   - **Fallback time scale:** $t^{-5/9}$
   - $L_{\text{EE}} \propto (1 + \frac{t}{\tau_{\text{EE}}})^{40/9}$

   (Kisaka & Ioka 2015)

Assume that $E \propto \exp(-t/\tau_{\text{EE}})$ due to magnetic reconnection. ($E \propto B^2$) $L_{\text{EE}} \propto B^2 \propto \exp(-t/\tau_{\text{EE}})$

2. **Exponential rotation energy loss rate of a highly magnetized neutron star**

See also our paper on arXiv:1904.10775!

**Summary**

We analyzed the early X-ray light curve of selected 26 SGRBs with known redshift. The results of this study are as following:

1. The EXP model can describe the extended emission light curves following 23 of the 24 (~96%) selected SGRBs with a rest-frame e-folding time of 20–200 s, while it is hard for the PL model to explain them comprehensively.
2. The isotropic energy of the extended emission in 2–10 keV is smaller by 0–3 orders of magnitude than that of the prompt emission.
3. There is a strong anti-correlation Between $L_{\text{EE}}$ and $\tau_{\text{EE}}$ with a power-law index of $\sim -3.3$. 

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*We exclude GRB 090510 and 100816A whose fitting parameters are not constrained due to the poor statistics at early observation phase.