Exponential Temporal Decay of Extended Emissions in Short Gamma-Ray Bursts with a Possible Luminosity - E-folding Time Correlation

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abstract

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 8.2×10-6 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($\theta \sim 1/\Gamma \sim 0.01$)

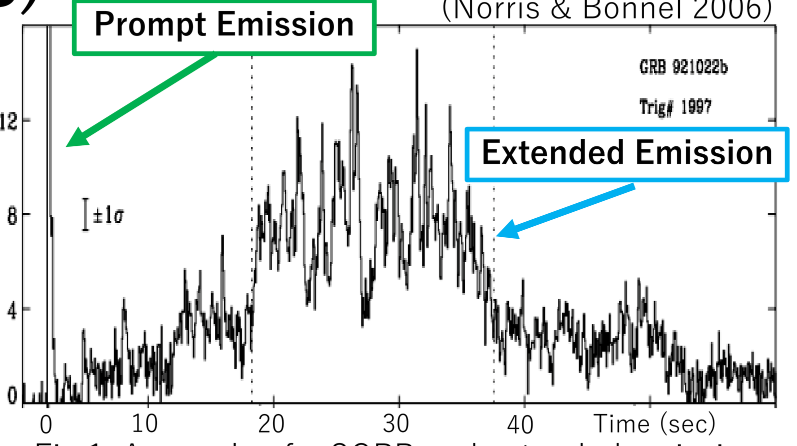

Fig 1. A sample of a SGRB and extended emission

(temporally) Extended X-ray Emission

- following some SGRBs **lasting about 100 sec**
- **comparable energy** with that of Prompt (in 15-150 keV)
- **rather wide** ($\theta > 10°$?; Bucciantini+ 2011)

➡ promising counterpart to GW

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 ($T_{90} < 2$ sec) and SGRB candidates ($T_{90} > 2$, but hard spectrum index and/or zero consistent spectral lag) detected by Burst Alart 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

26[*1] events with known redshift from 141 Swift SGRBs

[*1]GRB 050724, 051221A, 060614, 060801, 061006, 061201, 070714B, 070724, 070809, 071227, 080123, 080905A, 090426, 090510, 100117A, 100625A, 100816A, 101219A, 111117A, 130603B, 140903A, 150423A, 150424A, 160410A, 160624, and 160821B

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 this study, we compare the two models to **study which model is suitable for the extended emission** by performing light curve fitting.

EXP model: $L_{\rm EE}\exp(-t/\tau_{\rm EE}) \quad + \quad L_{\rm pl}\left(1+\frac{t}{T_{\rm pl}}\right)^{-\alpha_{\rm pl}}$

PL model : $L_{\rm EE}\left(1+\frac{t}{T_{\rm EE}}\right)^{-40/9} \quad + \quad L_{\rm pl}\left(1+\frac{t}{T_{\rm pl}}\right)^{-40/9}$

extended emission phase — plateau and afterglow phase

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)

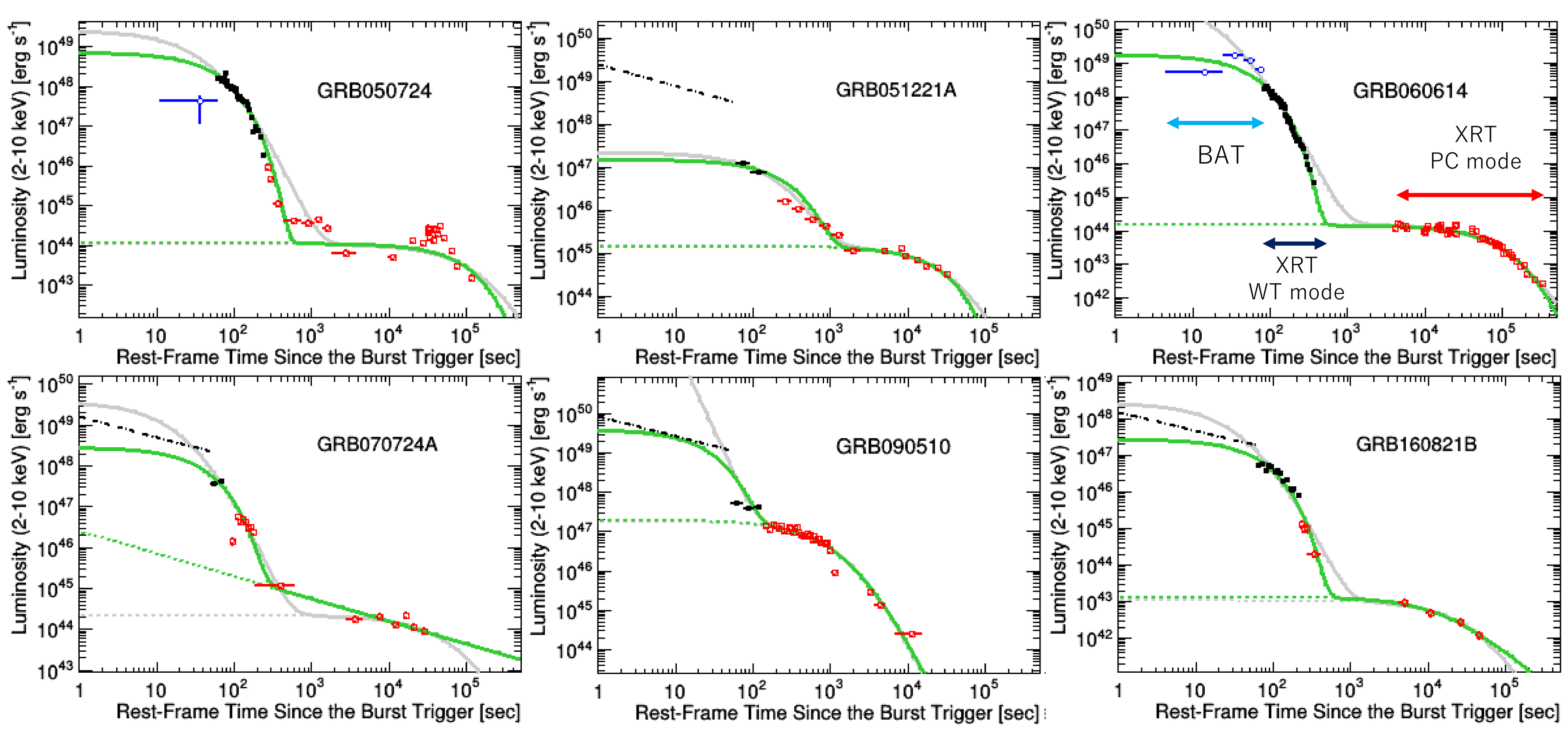

Fig 2. Samples of results of model fitting to the X-ray light curve of selected SGRBs. green: EXP model, glay: PL model, **dashed-dot line: Detection limit line of the Swift/BAT**

From the fitting results, such as χ^2_ν, we find that **23 of the 24[*2] 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

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

4. Discussion

Energy Comparison with That of Prompt Emission

Estimate the Isotropic Energy

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

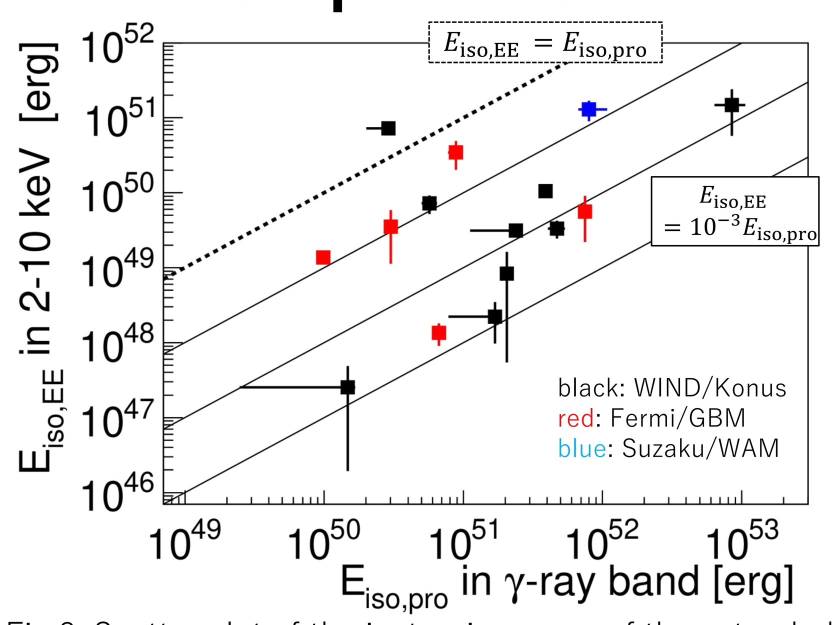

Fig 3. Scatter plot of the isotropic energy of the extended (2-10 keV) and prompt (γ-ray band) emissions

$$E_{\rm iso,EE,(2-10\ keV)} \sim 10^{-3\sim0}\ E_{\rm iso,prompt,(\gamma-ray\ band)}$$

$L_{\rm EE} - \tau_{\rm EE}$ Correlation

- $\tau_{\rm EE} = 20 - 200$ sec
- strong anti-correlation
  Spearman's rank order:-0.78
  chance probability: **8.6×10-6**
- $L_{\rm EE}(\tau_{\rm EE}) \propto \tau_{\rm EE}^{-3.3\pm0.1}$

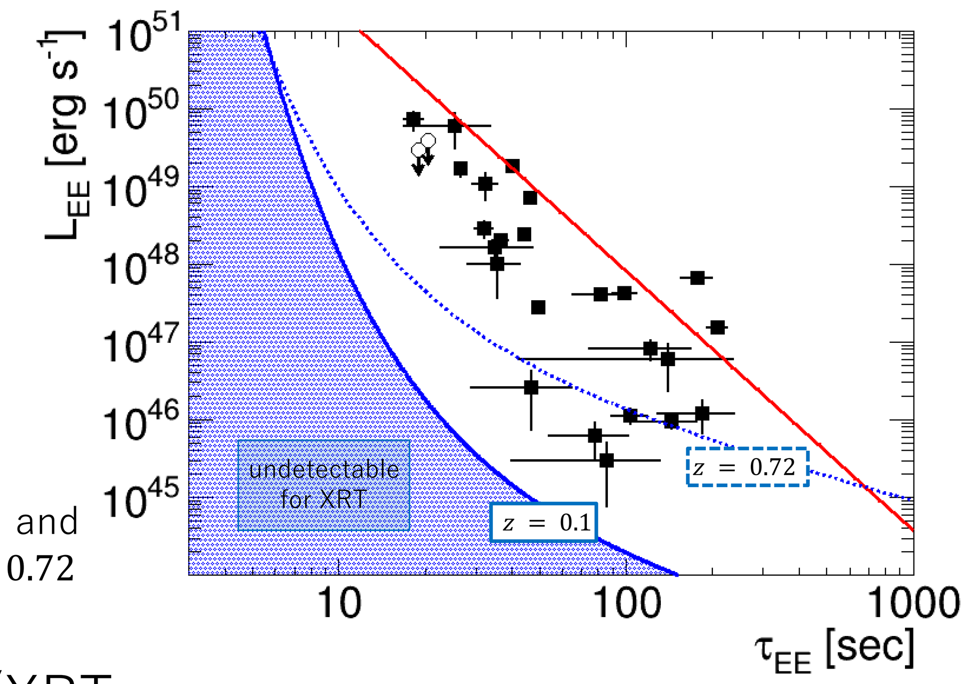

Fig 4. Scatter plot of $L_{\rm EE} - \tau_{\rm EE}$. (red) power-law fit, (blue solid and dashed): $L_{\rm XRT}(\tau_{\rm EE})$ of $z = 0.1$ and $z = 0.72$

Observation bias of the Swift/XRT

Detectable extended emissions would have a larger normalization $L_{\rm EE}$ than the detection limit of the XRT, $L_{XRT}(\tau_{\rm EE})$, described as

$$L_{\rm XRT}(\tau_{\rm EE}) = \frac{4\pi d_L^2 F_{\rm XRT}\tau_{\rm EE}}{\int_{T_{\rm start}/(1+z)}^{T_{\rm start}/(1+z)+\tau_{\rm EE}} \exp(-t/\tau_{\rm EE})\,dt}$$

$L(t) \sim L_{\rm EE}\exp(-t/\tau_{\rm EE})$
$F_{\rm XRT} = 2\times10^{-10}(1\ s/T)$ erg/cm2 /s (Burrouws+ 2005)
$T_{\rm start} = 80$ sec : observation start time

The extended emissions with $\tau_{\rm EE} \sim 20$ sec are brighter than $L_{\rm XRT}(\tau_{\rm EE})$ of $z = 0.72$ (averaged value) by a factor of ~10.

The correlation is intrinsic with no observation bias

5. Physical Origin

Exponential decay model of Extended Emissions

1. Fallback accretion onto a disk surrounding a black hole with an exponentially decaying magnetic flux by such as magnetic reconnection.

- Jet Luminosity: $L_{\rm BZ} \propto B^2$ (Blandford & Znajek 1997)
- Fallback time scale $t^{-5/3}$

$L_{\rm BZ} \propto \left(1+\frac{t}{T}\right)^{-40/9}$ (Kisaka & Ioka 2015)

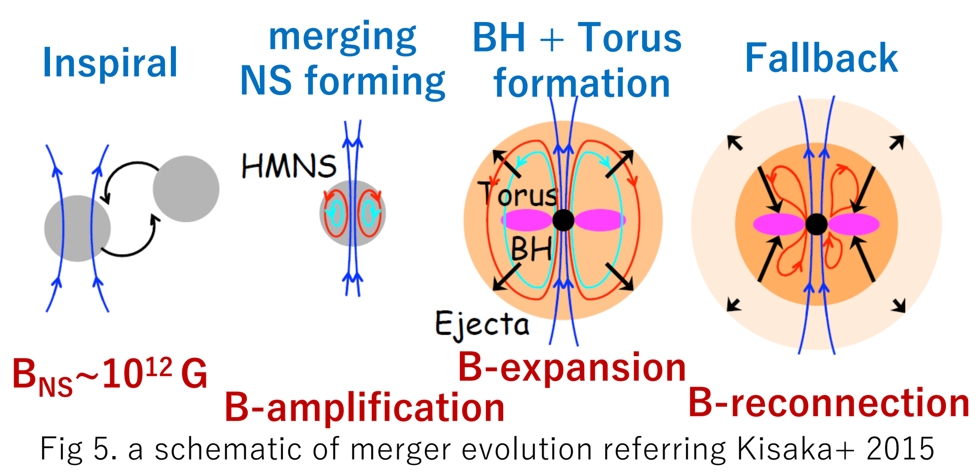

Fig 5. a schematic of merger evolution referring Kisaka+ 2015

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

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_{EE} and τ_{EE}** with a power-law index of ~−3.3.