A large-energy relativistic jet model for GRB 080710 producing bright achromatic afterglow.

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ABSTRACT

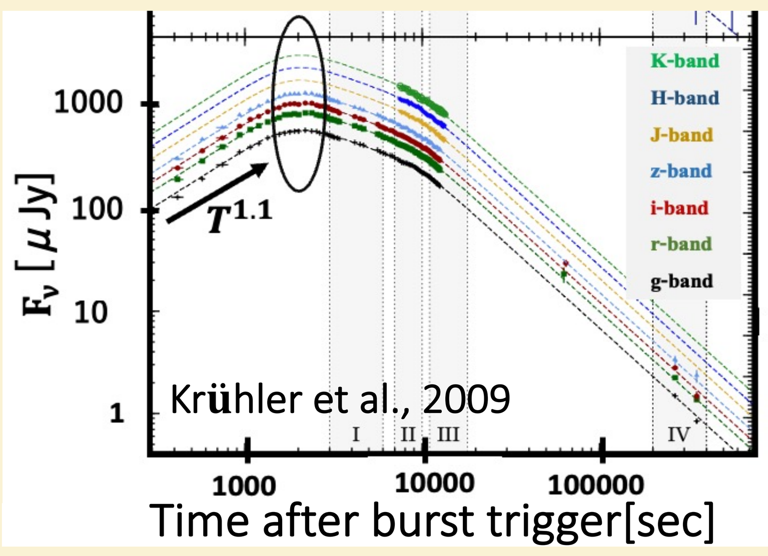
We present a possible theoretical interpretation of the observed afterglow emission of long gamma-ray burst GRB 080710. Assuming that the angular distribution of the outflow energy is top-hat or Gaussian-shaped, we calculate the observed light curves of the synchrotron emission from the relativistic jets and explore the model parameters that explain the observed data. It is found that a narrowly (half opening half $\sim \mathbf{0.02}$ rad) collimated Gaussian-shaped jet with large isotropic-equivalent energy ($\sim \mathbf{10^{55}}$erg) is the most plausible model to reproduce the observed afterglow behavior. Namely, the off-axis afterglow scenario to the achromatic peak is unlikely. For details, see our paper, Obayashi et al.2023 [1] .

1. Introduction

Why GRB 080710 [2]?

- Opt/IR afterglows show achromatic peak at $\mathbf{2.2 \times 10^3}$ s.
- Opt/IR afterglow before the peak increases ($\boldsymbol{F_\nu \propto T^{1.1}}$).

This event has been understood qualitatively as off-axis afterglow.



However,

- Prompt emission energy is as bright and hard as on-axis events.
- Rising slope as off-axis afterglow may be steeper than observed.

Let's fit data with off-axis structured jet model.

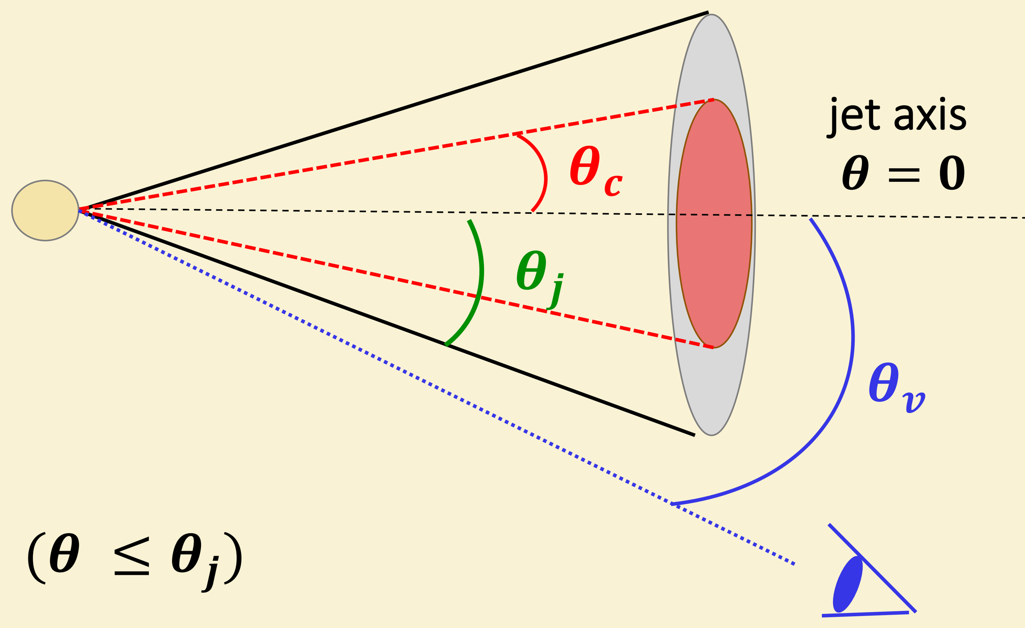
2. Afterglow Model

Dependence on jet structures and jet viewing angle is studied.

Two types of jet structures.

1. Top-hat jet (TH)

$$E(\theta) = \begin{cases} E_0 & (\theta \le \theta_j) \\ 0 & (\theta > \theta_j) \end{cases}$$



2. Gaussian jet

$$E(\theta) = \begin{cases} E_0 \exp\left(-\dfrac{\theta^2}{2\theta_c^2}\right) & (\theta \le \theta_j) \\ 0 & (\theta > \theta_j) \end{cases}$$

Both $\boldsymbol{\theta_j < \theta_v}$ and $\boldsymbol{\theta_j > \theta_v}$ are considered

- Gamma-Flat (GF) ; $\Gamma(\theta) = \Gamma_0$
- Gamma-Even-Mass (GEM) ; $\Gamma(\theta) = 1 + (\Gamma_0 - 1)\dfrac{E(\theta)}{E_0}$

Afterglowpy [3] is used to calculate the observed light curves.

3. Fitting Method

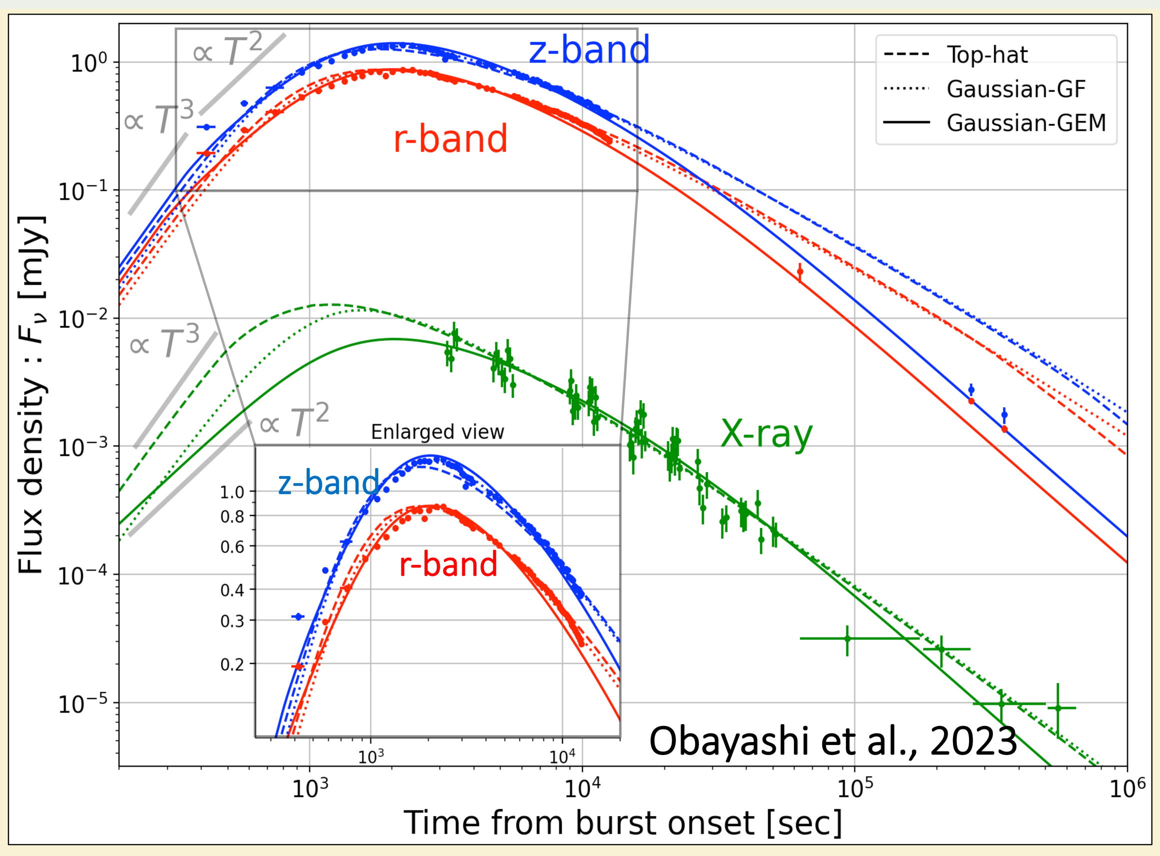
Using the Python MCMC module emcee [4], we perform a Bayesian estimation to fit the optical (r-band), infrared (z-band), and X-ray afterglow of GRB 080710.

Model parameters		Prior bounds
θ_c	Half-width of the jet core	[0.001, 0.5]
θ_j	Half-opening angle of jet	$[1, 2] \times \theta_c$
θ_v	Viewing angle	$[0, 1.5] \times \theta_j$
Γ_0	Initial Lorentz factor jet central axis	[10, 500]
E_0	Initial isotropic equivalent energy on-axis	$[10^{50}, 10^{55}]$
n_0	Number density of ISM	$[10^{-4}, 10^{2}]$
p	Electron distribution power-law index	[2.01, 2.9]
ε_B	Thermal energy fraction in electrons	$[10^{-3}, 10^{-0.3}]$
ε_e	Thermal energy fraction in magnetic field	$[10^{-5}, 10^{-0.3}]$
ξ_N	Fraction of electrons that get accelerated	$[10^{-2}, 10^{0}]$

4. Result

Best-fit params. (GEM).

θ_v [rad]	0.0001
θ_j [rad]	0.0242
θ_c [rad]	0.0121
Γ_0	104
E_0 [erg]	9.98×10^{54}
n_0 [cm^{-3}]	3.47×10^{-2}
p	2.01
ε_B	4.99×10^{-1}
ε_e	1.12×10^{-2}
ξ_N	0.543



- Opt/IR achromatic peak was reproduced by TH, GF, and GEM.
- Three models are different after $\sim \mathbf{10^4}$s for opt/IR.
  →Only GEM explains the data at $\sim \mathbf{3\times10^5}$s.
- The rising part was not explained yet ($\boldsymbol{\chi^2/d.o.f}$ →TH:1942/(96-9), GF:2124/(96-10), GEM:900/(96-10)), but the GEM is preferred.

5. Discussion

- On-axis afterglow is consistent with the typical prompt emission.
- In the TH, GF, and GEM, the optical/infrared achromatic peak is explained by the jet deceleration.
  - Huge isotropic equivalent energy value of $\boldsymbol{E_0 \sim 10^{55}}$erg.
  - Collimation-corrected jet energy is normal due to the narrow jet.
  - Efficiency of prompt emission is much smaller than inferred values.

$$\eta_\gamma = \frac{E_{\gamma,\mathrm{iso}}}{[E_{\gamma,\mathrm{iso}} + E(\theta_{\mathrm{obs}})]} \sim 6\times10^{-4}$$

→ Low prompt efficiency is, for example, explained by less turbulent flow in the GRB jet??

- The r-band and z-band fluxes roughly $\boldsymbol{F_\nu \propto T^2}$ for GEM.
  - They implicate the free expansion phase before the peak.
  - The GEM is better than TH and GF ($\boldsymbol{F_\nu \propto T^3}$) to fit observed data.

→ More gradual flux increase for better fit to the observed data.

- A strong point of our GEM is that the decay slope immediately after the peak is steep due to the whole jet emission coming to observer.

$$\Gamma(\theta_j)\left|\theta_{obs} + \theta_j\right| < 1.$$

- Huge energy and narrow jet are similar to those of GRB 221009A .

6. Conclusion & Future Work

Using Bayesian inference with MCMC, we have found a possible scenario of GRB 080710 showing achromatic optical/infrared peak at $\mathbf{2.2 \times 10^3}$ s. Contrary to the claim of off-axis afterglow model [2], we find that on-axis structured narrow jet model and the large value of the initial isotropic equivalent energy in all models. The best jet structure is the GEM but does not perfectly.

- More complicated jet structure might be necessary.
  → The non-uniform circumburst medium like wind profile?
- Achromatic peak events like GRB 080710 have been detected GRBs 050408, 071031, and 080603A.

References

[1] Obayashi et al., 2023 [arXiv:2310.08900]
[2] Krühler et al., 2009 , A&A, 508, 593.
[3] Sari, Piran, & Narayan, 1998, ApJL, 497, L17.
[4] Ryan et al., 2020, ApJ, 896, 166.
[5] Foreman-Mackey et al., 2013, PASP, 125, 306.