Multi-Wavelength Modelling of Low-Luminosity Gamma-Ray Burst Afterglows in the Forward-Shock Synchrotron Framework

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Abstract

We present a multi-wavelength modeling analysis of Low-Luminosity Gamma-Ray Burst (LLGRB) afterglows within the standard forward-shock synchrotron framework. Synthetic light curves are generated across radio (10^9 Hz), UV (10^{15} Hz), X-ray (10^{18} Hz), and γ-ray (10^{20} Hz) bands using physically motivated parameters. The model predicts a common peak time of □0.01 days across radio, UV, and X-ray bands. Radio, UV, and X-ray bands follow similar decay slopes (α ≈ −1.36 to −1.38), indicating a shared slow-cooling synchrotron regime, while γ-rays decline more steeply (α ≈ −6.2). When compared to observed LLGRB data, our modeling reproduces the strong E_{iso}–L_{iso} correlation and the E_{iso}–z dependence reported in the literature. These results support the forward-shock model as a robust explanation for broadband GRB afterglows.

Introduction

What Are LLGRBs?

- E_{iso} = 10^{48} – 10^{50} erg (2–4 orders below classical GRBs)
- **z** = 0.3 (predominantly local Universe)
- T_{90} > 10 s, smooth single-peaked light curves
- **Soft spectra**, E_{peak} often in X-ray band
- **Supernova association**: Type Ic-BL (GRB 980425/SN 1998bw, GRB 060218/SN 2006aj)
- **Mildly relativistic**: Γ = 2–10 (vs. Γ =100 for classical GRBs)

Scientific Motivation: LLGRBs provide unique insights into relativistic outflows, shock microphysics, and the GRB-supernova connection. Their high local rate makes them potential sources of ultra-high-energy cosmic rays.

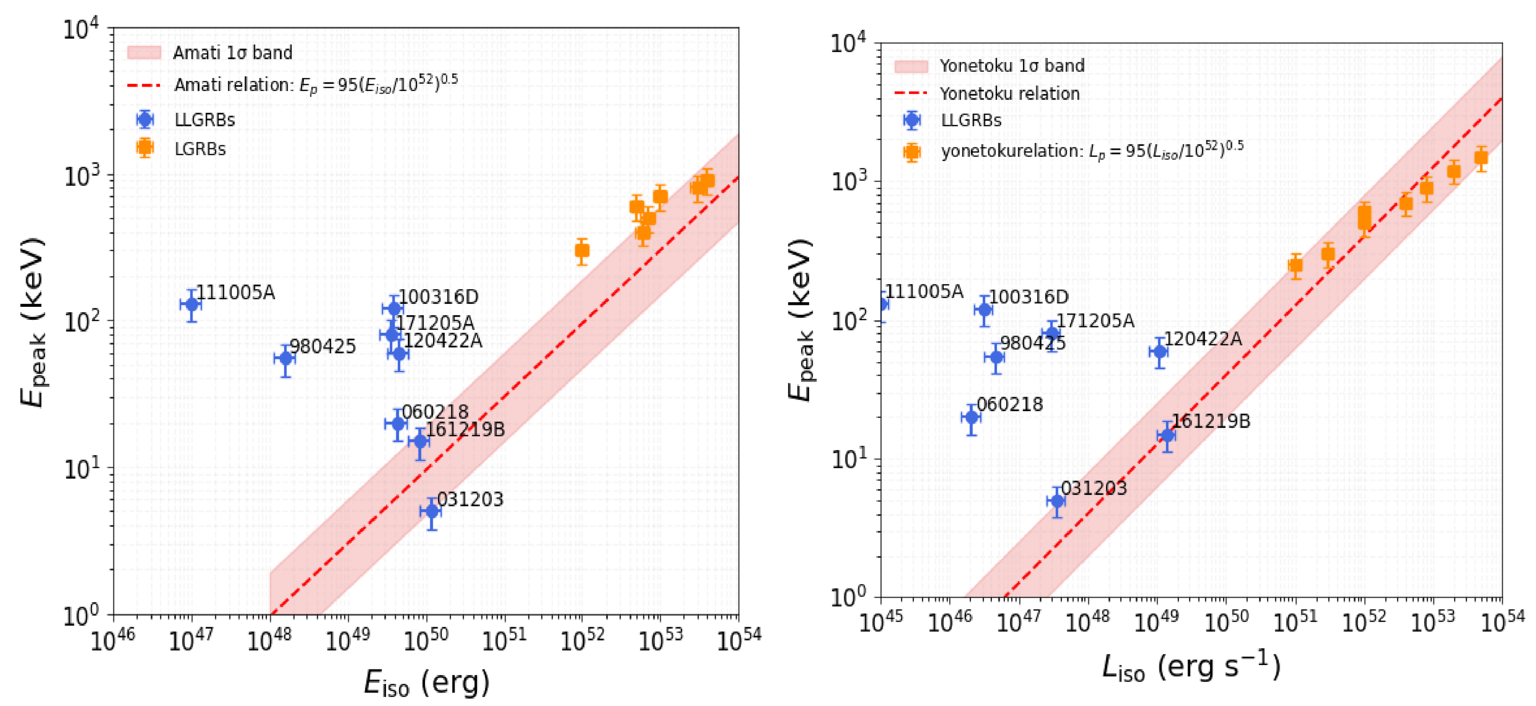


Figure 1: (Left) Amati relation (E_{peak} vs. E_{iso}) and (Right) Yonetoku relation (E_{peak} vs. L_{iso}). LLGRBs occupy the low-energy extension of both correlations.

AIM: To model multi-wavelength afterglows for LLGRBs, by exploring empirical correlations among isotropic energy (E_{iso}), luminosity (L_{iso}), flux (F_{peak}), and evaluate how the observed light curves compare to the theoretical forward-shock synchrotron framework.

Theoretical Framework

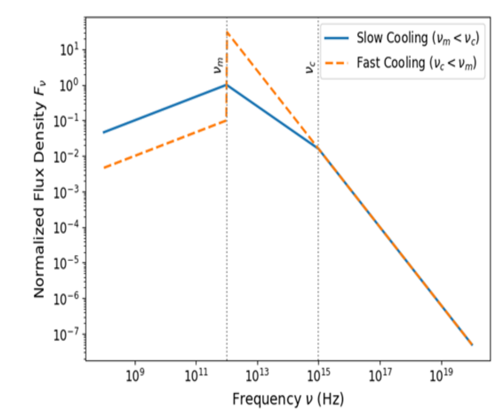
Forward Shock Dynamics: For a blast wave expanding into a uniform interstellar medium (ISM), the Lorentz factor Γ evolves with observer time t

$$\Gamma(t) \approx 6.2 \left(\frac{E_{\rm iso,49}}{n_0}\right)^{1/8} \left(\frac{t}{10^3\ {\rm s}}\right)^{-3/8} (1+z)^{3/8}$$

Characteristic Synchrotron Frequencies: The general form for the synchrotron flux density at a given time is given by:

$$F_\nu(t) = F_{\nu,\max}(t) \times S(\nu, \nu_m(t), \nu_c(t))$$

$$S(\nu,\nu_m,\nu_c) \propto \begin{cases} \left(\frac{\nu}{\nu_m}\right)^{1/3}, & \nu < \nu_m, \\ \left(\frac{\nu}{\nu_m}\right)^{-(p-1)/2}, & \nu_m < \nu < \nu_c \\ \left(\frac{\nu_c}{\nu_m}\right)^{-(p-1)/2} \left(\frac{\nu}{\nu_c}\right)^{-p/2}, & \nu > \nu_c. \end{cases}$$



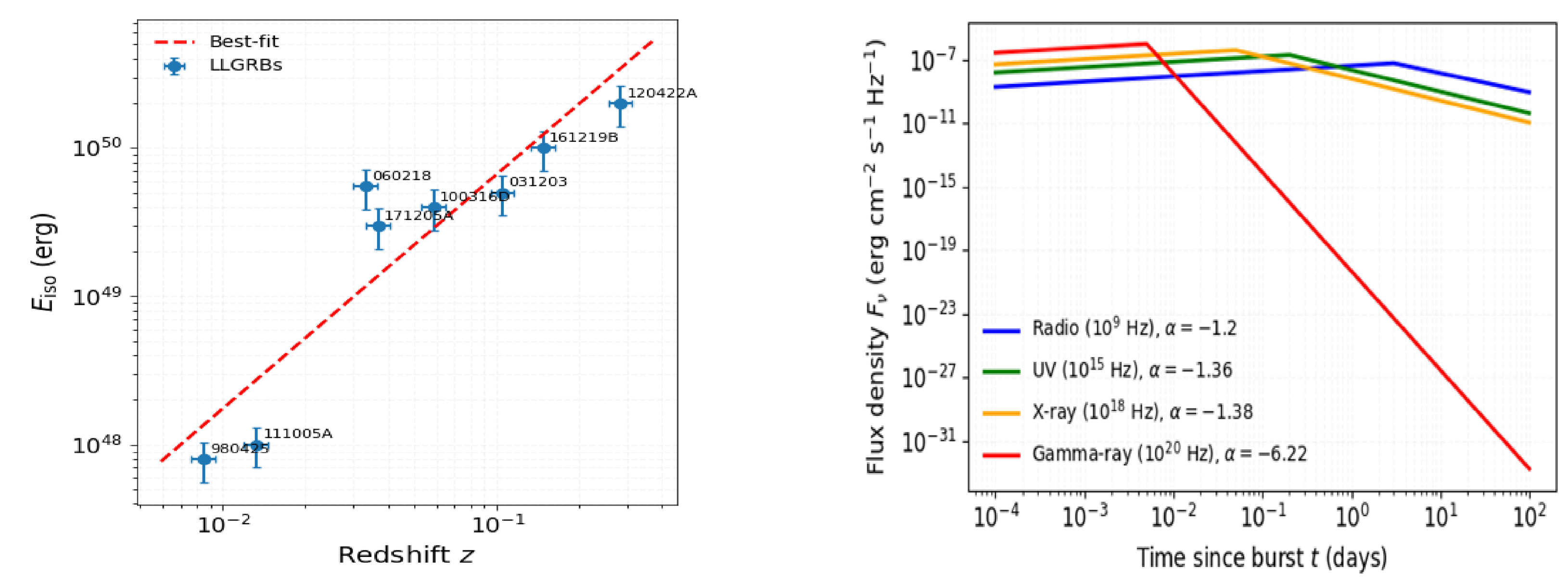


Figure 2: Left: Isotropic-equivalent energy E_{iso} as a function of redshift z. The correlation suggests a luminosity-dependent detection bias or intrinsic evolution. **Right:** Broadband spectrum at t = 1 day. Spectral indices are consistent with p ≈ 2.2 in the slow-cooling regime.

Data and Methods

Model Parameters

- E_{iso} = 10^{48}–10^{50} erg
- n_0= 0.1 –10 cm^{-3}
- **p** = 2.2
- ε_e = 0.1, ε_B = 0.01
- **z** = 0.0085 – 0.283 (from observed LLGRB sample)

Observed LLGRB Sample (8 bursts)

GRB 980425, GRB 031203, GRB 060218, GRB 100316D, GRB 171205A, GRB 111005A, GRB 120422A, GRB 161219B

Results

Temporal Decay

- **Common peak time:** t_p ≈ 0.01 days (radio, UV, X-ray)
- **Decay slopes:** α ≈ −1.36 to −1.38 (radio, UV, X-ray)
- **γ-ray decay:** α ≈ −6.2 (prompt emission cessation)
- Matches theory: α = (3p-3)/4 ≈ −1.4 for p = 2.2

Spectral Indices

- **β ≈ −0.6** ($\nu_m < \nu < \nu_c$)
- **β ≈ −1.1** ($\nu > \nu_c$)

Discussion

Physical Interpretation

- **Slow-Cooling Regime:** α ≈ −1.37 indicates $\nu_m < \nu_{obs} < \nu_c$
- **Electron Index:** p ≈ 2.2 (diffusive shock acceleration)
- **Uniform ISM:** Favored over wind-like profile

LLGRBs in Context

- **Distinct Population:** Weaker jets or larger radii
- **Continuum Population:** Low-luminosity tail of classical GRBs (off-axis viewing)

Strong E_{iso}–L_{iso} correlation suggests stable radiative efficiency.

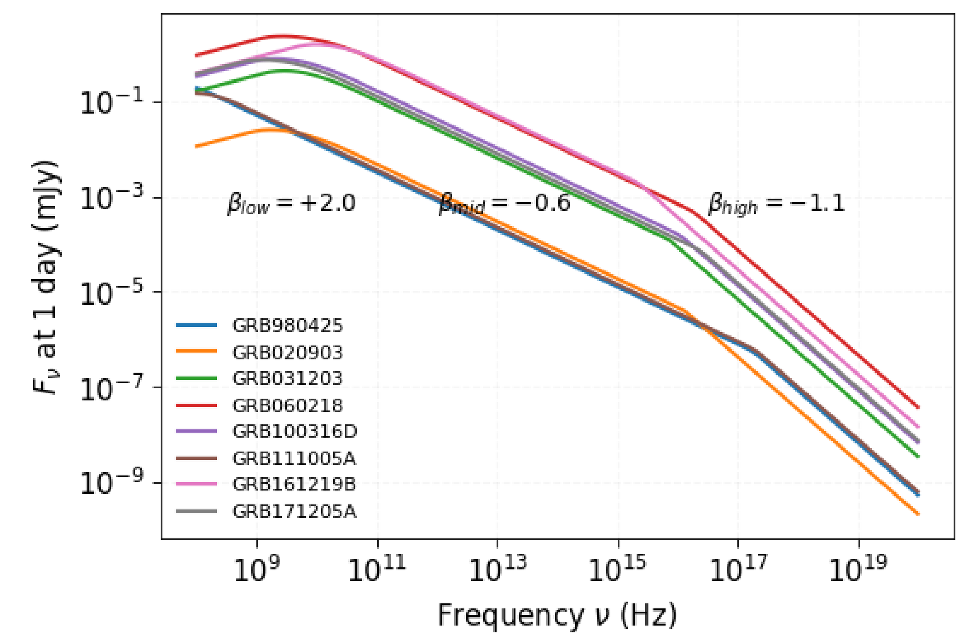


Figure. 2: Broadband afterglow spectrum of a representative LLGRB constructed at a fixed epoch (t=1 dy after the burst). The flux density F_ν is shown as a function of observing frequency (ν) on log scale regimes

SUMMARY & FUTURE DIRECTIONS

- Forward-shock model reproduces LLGRB afterglows
- Radio, UV, X-ray: common peak (~0.01 days), similar decay (α ≈ −1.37)
- γ-ray decays steeply (α ≈ −6.2)
- Spectral indices imply p ≈ 2.2, slow-cooling regime
- LLGRBs occupy low-energy extension of Amati/Yonetoku relations
- Strong E_{iso}–L_{iso} correlation

Future Work

- Bayesian parameter inference with multi-wavelength data
- Systematic LLGRB vs. classical GRB comparison
- Expand sample with SVOM, Einstein Probe
- Include inverse Compton/SSC components

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