Multi-wavelength Afterglow Analysis of GRB 221009A: Unveiling the Evolution of a Cooling Break in a Wind-like Medium

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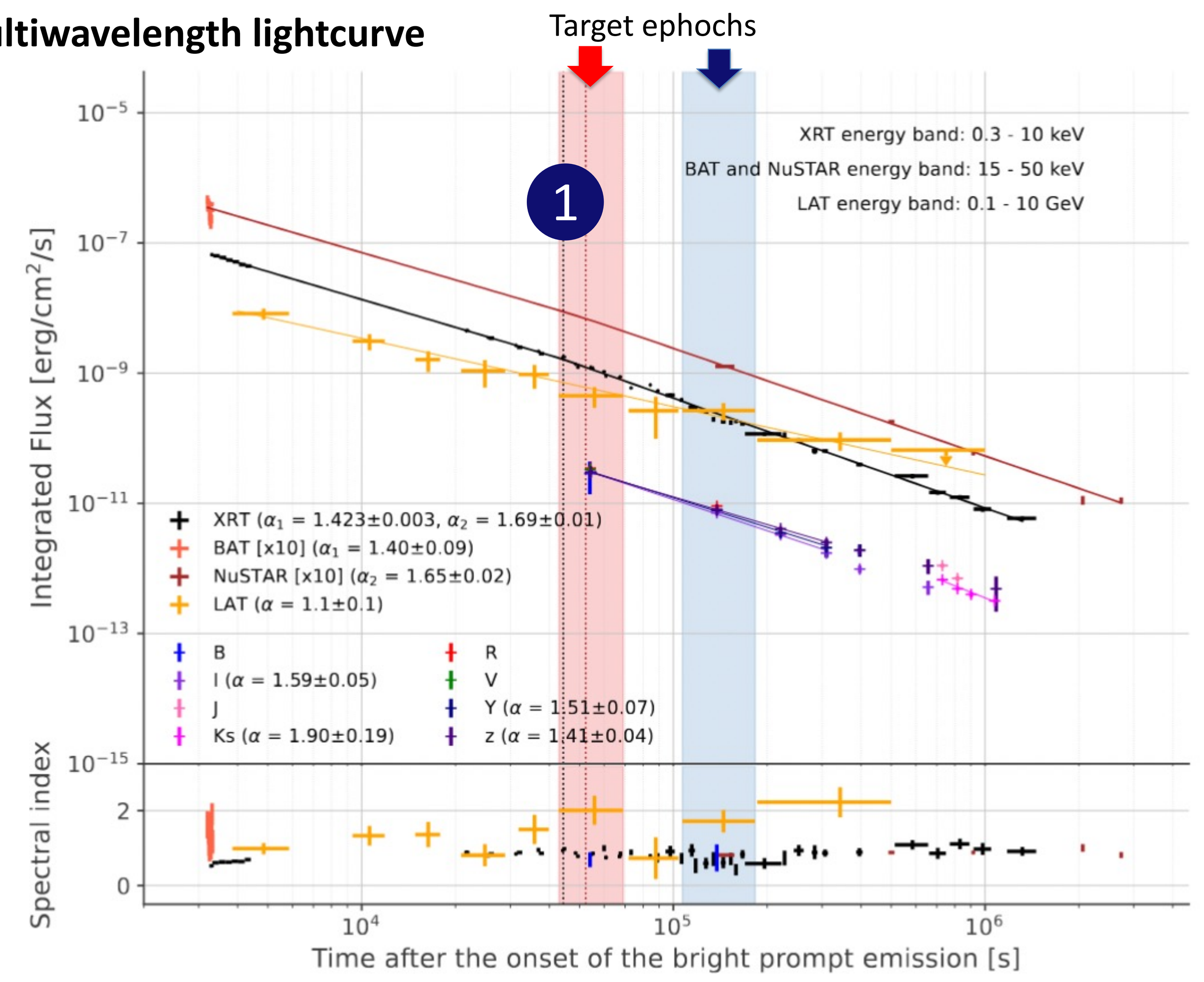
Gamma-ray bursts (GRBs) are the most energetic explosions in the universe, and their afterglow emission provides an opportunity to probe the physics of relativistic shock waves in an extreme environment. Several key pieces for completing the picture of the GRB afterglow physics are still missing, including jet properties, emission mechanism, and particle acceleration. Here we present a study of the afterglow emission of GRB 221009A, the most energetic GRB ever observed. Using optical, X-ray, and gamma-ray data up to approximately two days after the trigger, we trace the evolution of the multiwavelength spectrum and the physical parameters behind the emission process.

Individual observations

Dataset

Wavelength	Instrument	Energy band	Observation	Analysis
Optical	SomangNet	Ks, Y, z, I, R, V, B	0.6 - 12 days	In-house code (gpPy)
X-ray	Swift XRT	0.5– 10 keV	About 3,000s to 16 days	Xspec
X-ray	NuSTAR	3 – 79 keV	1.6 – 31 days	Xspec
γ-ray	Fermi LAT	0.1-10 GeV	Up to 2 days	fermipy

Multiwavelength lightcurve



Spectral and temporal indices of two epochs

Note that $f_\nu \propto \nu^{-\beta} t^{-\alpha}$

Instrument	Energy band	Epoch	α	β
LOAO	1.3–2.9 eV	1	1.59 ± 0.05 [a]	0.69 ± 0.20 [b]
		2		0.73 ± 0.36 [b]
Swift-XRT	0.3–10 keV	1	1.688 ± 0.010	0.843 ± 0.014
		2		0.723 ± 0.040
NuSTAR	3–79 keV	2	1.654 ± 0.018	0.815 ± 0.009
Fermi-LAT	0.1–10 GeV	1	1.04 ± 0.06	2.01 ± 0.39
		2		1.72 ± 0.30

Errors correspond to 1-σ confidence region.

1. **Normal decay phase: afterglow**
   Temporal indices from optical and X-ray energy bands are consistent.
   $\alpha \sim 1.5 - 1.7$
2. **Photon index remains constant in the optical and X-ray energy band.**
   $\beta = \Gamma - 1 \sim 0.7 - 0.8$
3. **The indices from GeV emission are very different from the others**

Multiwavelength analysis

Model

$$\frac{dN}{dE} = K\left(\left(\frac{E}{E_b}\right)^{s\Gamma_1} + \left(\frac{E}{E_b}\right)^{s(\Gamma_1+0.5)}\right)^{-1/s} e^{-E/E_c}$$

Synchrotron model with its maximum cutoff

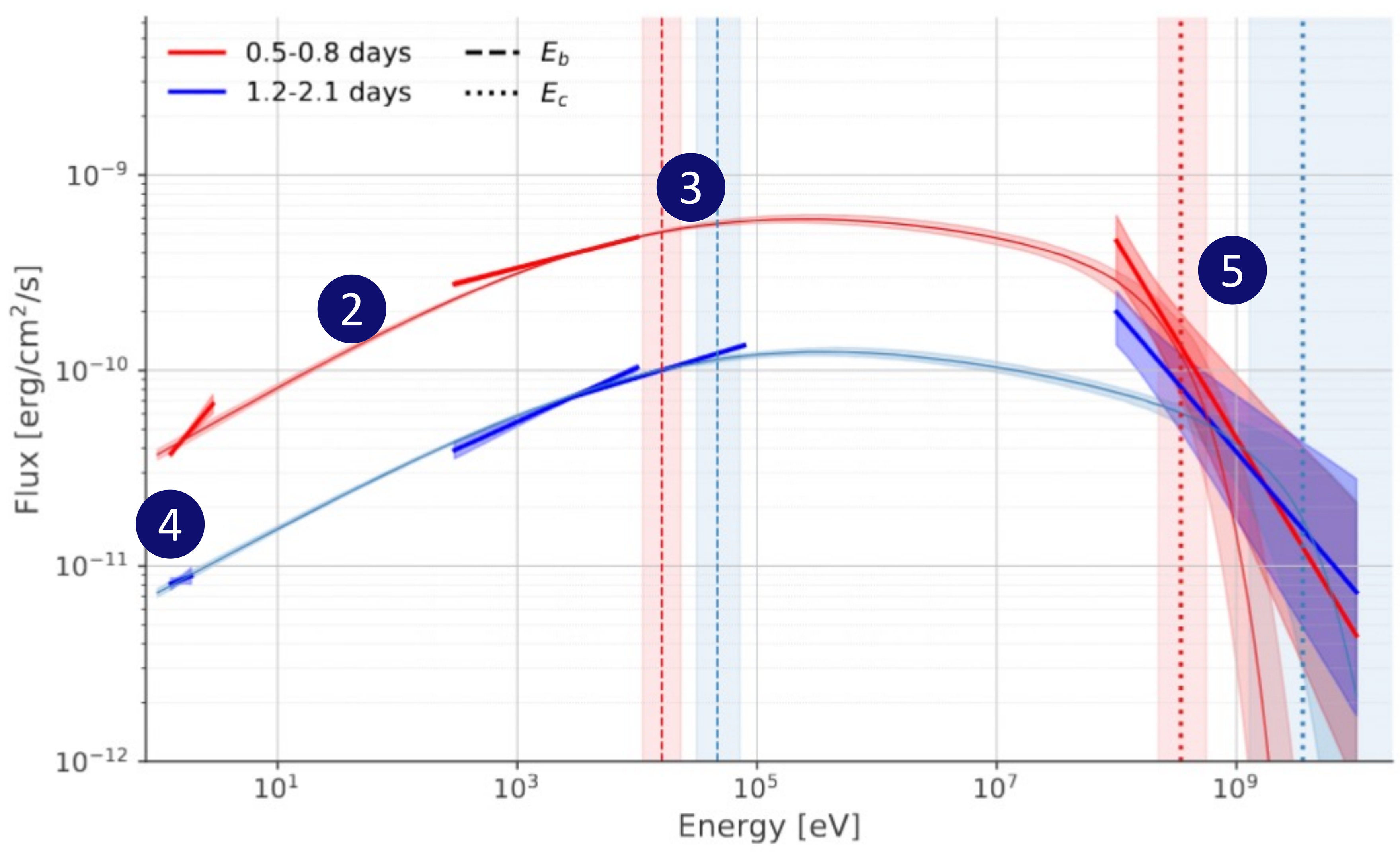
See J. Granot & R. Sari 2002, Kumar et al., 2012

Analysis tool

3ML Multi-Mission Maximum Likelihood Framework

See Klinger et al., 2023

Spectral energy distribution



Best-fit parameters

Epoch	K [1/cm²/s/keV]	E_b [keV]	Γ_1	E_c [GeV]	N_H [$\times10^{22}$ atoms/cm²]	A_ν	C_x
1	$0.1958^{+0.0028}_{-0.0029}$	$16.0^{+7.1}_{-4.9}$	$1.635^{+0.010}_{-0.011}$	$0.34^{+0.22}_{-0.12}$	$1.112^{+0.021}_{-0.021}$	$0.62^{+0.13}_{-0.12}$	
2	$0.0366^{+0.0007}_{-0.0006}$	$46.8^{+25.0}_{-15.5}$	$1.658^{+0.012}_{-0.012}$	$3.57^{+19.42}_{-2.29}$	$1.401^{+0.045}_{-0.048}$	$0.10^{+0.10}_{-0.06}$	$0.95^{+0.02}_{-0.01}$

Findings and Implications

1. **Temporal breaks are observed in the X-ray band, with the temporal break in Swift XRT occurring earlier than in NuSTAR. This chromatic feature suggests that these breaks are not due to a jet break or jet structure. Instead, they are related to the evolution of the cooling frequency ν_c over time. See also Mark 3.**

2. **The spectral indices from the two-time epochs are consistent, with $\Gamma \simeq 1.6$, indicating that the optical and soft X-ray energy bands remain within the same cooling regime during both time epochs. This also suggests that the electron spectral index is $p = 2\Gamma_1 - 1 = 2.29 \pm 0.02$**

3. **We identify the intriguing evolution of a break energy, which is well interpreted as the cooling frequency, ν_c. Compared to the previous works, this evolution is relatively clear, agreeing with the theoretical expectation. From its evolution, the circumburst density profile is determined, $k = 2.5 \pm 0.4$ where $\rho \propto r^{-k}$. See also Mark 4**

4. **Since the optical emission originates from the same cooling regime, the circumburst density profile can be independently estimated. With the estimated value of p (Mark 2) and the flux decay at 1 eV, $k = 2.4 \pm 0.1$. This result is consistent with the findings in Mark 3. This density profile is softer than the wind-like profile (k =2), which suggests that further understanding of the circumburst medium is needed.**

5. **While the high-energy cutoff is commonly observed during the prompt emission phase, this work shows its presence in the afterglow approximately 1–2 days for the first time. The high-energy cutoff can be interpreted as the maximum synchrotron limit due to the inefficient electron acceleration at a high-energy regime. With this interpretation, we can estimate the bulk Lorentz factor, $\Gamma_{bulk} \sim 4 - 40$.**