GRB 210610B: The Internal and External Plateau as Evidence for the Delayed Outflow of Magnetar (Postprint)

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Date: 2024-08-14T00:00:00+00:00

Abstract

After launching a jet, outflows of magnetar were used to account for the achromatic plateau of afterglow and the early X-ray flux plateau known as “internal plateau”. The lack of detecting magnetic dipole emission together with the energy injection feature in a single observation poses confusion until the long gamma-ray burst (GRB) 210610B is detected. GRB 210610B is presented with an optical bump following an early X-ray plateau during the afterglow phase. The plateau followed by a steep decline flux overlays in the steadily decaying X-ray flux with index αX,1 2.06, indicating an internal origin and that can be fitted by the spin-down luminosity law with the initial plateau luminosity and the characteristic spin-down timescale T 2818 s. A subsequent bump begins at 4000 s in the R band with a rising index αR,1 − 0.30 and peaks at 14125 s, after which a decay index αR,2 0.87 and finally transiting to a steep decay with αR,3 1.77 achieve the closure relation of the external shock for the normal decay phase as well as the magnetar spin-down energy injection phase, provided that the average value of the photon index $\Gamma\gamma = 1.80$ derived from the spectral energy distributions (SEDs) between the X-ray and optical afterglow. The closure relation also works for the late X-ray flux. Akin to the traditional picture of GRB, the outflow powers the early X-ray plateau by dissipating energy internally and collides with the leading decelerating blast burst as time goes on, which could interpret the exotic feature of GRB 210610B. We carry out a Markov Chain Monte Carlo simulation and obtain a set of best parameters: „ EK,iso 4.6 × 1053erg, Γ0 832, A* 0.10, Linj,0 3.55 × 1050erg s−1. The artificial light curve can fit the afterglow data well. After that, we estimated the average Lorentz factor and the X-ray radiation efficiency of the later ejecta are 35% and 0.13%, respectively.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:075013 (11pp), 2024 July

https://doi.org/10.1088/1674-4527/ad4d3a

GRB 210610B: The Internal and External Plateau as Evidence for the Delayed Outflow of Magnetar

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Received 2024 March 8; revised 2024 May 1; accepted 2024 May 7; published 2024 July 8

Abstract

Following the launch of a relativistic jet, magnetar outflows have been invoked to explain both the achromatic plateau in GRB afterglows and the early X-ray flux plateau known as the "internal plateau." However, the lack of simultaneous detection of magnetic dipole emission and energy injection features in a single observation has posed a puzzle—until the detection of the long gamma-ray burst (GRB) 210610B. GRB 210610B exhibits an optical bump following an early X-ray plateau during its afterglow phase. The plateau, which is followed by a steep flux decline, is superimposed on a steadily decaying X-ray flux with index α_X,1 2.06, indicating an internal origin that can be fitted by the spin-down luminosity law with a characteristic spin-down timescale T 2818 s. A subsequent bump in the R band begins at 4000 s with a rising index α_R,1 −0.30, peaks at 14125 s, and then decays with index α_R,2 0.87 before transitioning to a steep decay with *αR,3 1.77. This behavior satisfies the closure relations of the external shock model for both the normal decay phase and the magnetar spin-down energy injection phase, provided that the average* *photon index derived from the spectral energy distributions (SEDs) between X-ray and optical afterglows is* $\Gamma\gamma = 1.80$. The closure relation also holds for the late X-ray flux. Similar to the traditional GRB picture, the outflow powers the early X-ray plateau through internal energy dissipation and subsequently collides with the leading decelerating blast wave, which can interpret the exotic features of GRB 210610B.

We perform Markov Chain Monte Carlo simulations and obtain a set of best-fit parameters: _B 4.7 × 10^{-5}, _e 0.15, E_K,iso 4.6 × 10^{53} erg, Γ_0 832, A_* 0.10, L_{inj},0 3.55 × 10^{50} erg s^{-1}. The synthetic light curve fits the afterglow data well. From this, we estimate that the average Lorentz factor of the later ejecta is 35% and its X-ray radiation efficiency is 0.13%.

Key words: (stars:) gamma-ray burst: individual (GRB 210610B) – (stars:) gamma-ray burst: general – stars: jets

1. Introduction

Gamma-ray bursts (GRBs), signaling the most energetic explosions in the universe, have at least two distinct physical origins: the death of massive stripped-envelope stars or the merger of binary compact objects. The central engine driving GRBs could be either a newborn black hole with hyper-accretion or a rapidly spinning, highly magnetized neutron star (also known as a millisecond magnetar). Both entities can launch a relativistic jet, where internal interactions within the outflow produce sub-MeV emission while subsequent interactions with the circumburst medium generate the afterglow.

Although afterglows were theoretically predicted before their detection by BeppoSAX, the launch of X-ray astronomy satellites—particularly the Swift Gamma-Ray Burst Explorer—enabled systematic studies that have illuminated afterglow properties. X-ray afterglow light curves can typically be divided into four segments: (I) an early-time steep decay phase, generally interpreted as the curvature effect due to delayed photon propagation from high latitudes; (II) a shallow decay phase from continuous energy injection into the blast wave, also known as the "external plateau"; (III) a normal decay phase consistent with external shock expectations; and (IV) a late-time decay steeper than normal due to jet break. Some unusual afterglow features manifest as extended engine activity, such as erratic X-ray flares and early-time X-ray plateaus superimposed on a background power-law decay component (known as "internal plateau").

The energy injection model has been widely adopted to interpret the "external plateau," which appears in late-time afterglows with various forms. One popular injection mechanism is rotational energy from a newborn magnetar via dipole radiation that injects energy into the external shock. In this scenario, one should detect accompanying emission from internal dissipation of the magnetar wind; however, such emission has never been detected in previous bursts. This puzzle not only complicates explanations of the external shock plateau but also motivates searches for this signal. Fortunately, GRB 210610B—characterized by a long-lasting optical plateau—provides an ideal example that meets these expectations. It shows an X-ray plateau superimposed on stable decay, followed by an abrupt decline at the plateau's end. This picture is inconsistent with the standard forward shock afterglow model and instead calls for prolonged central engine activity.

This paper is organized as follows: Section 2 presents observational information for GRB 210610B. Section 3 provides temporal and spectral analysis results. Section 4 describes the modeling methods and results. Section 5 concludes with a discussion. We define flux evolution as F $t^{-\alpha}$ $^{-\beta}$ throughout this paper. A concordance cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, Ω_M = 0.30, and Ω_Λ = 0.70 is adopted for calculating X-ray plateau luminosities.

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2. Observations

GRB 210610B was triggered by the Burst Alert Telescope (BAT) onboard Swift on June 10, 2021, at 19:51:27 UT with T_{90} 69 s. The Gamma-Ray Burst Monitor (GBM) onboard Fermi had already triggered on GRB 210610B (trigger 645047470/210610827) at 19:51:05 UT (T_0) with T_{90} 55 s, 22 s before Swift's detection. The High Energy X-ray telescope (HE) onboard the Hard X-ray Modulation Telescope (HXMT) also triggered at 2021 June 10 19:49:47.510 UT, much earlier than other detectors. The light curves exhibited a complex multi-pulse profile [Figure 1: see original paper].

The X-ray Telescope (XRT) and UV-optical Telescope (UVOT) onboard Swift began observing the field at 83.9 s and 91 s after the BAT trigger, respectively. We downloaded BAT and XRT data from the Swift burst analyzer website, Fermi/GBM data from the Fermi FTP Archive, and HXMT data from the HXMT archive. Their light curves are shown in Figure 1. Both time-integrated and time-resolved GBM spectra were extracted using the Python package gt-Burst. Approximately 3.14 days after the trigger, we conducted optical follow-up observations using the Las Cumbres Observatory Global Telescope (LCOGT) 1.0 m Sinistro instruments, performing 5 × 300 s exposures in Bessel R filters. Data reduction followed standard IRAF routines. The photometric data are presented in Table 1 .

Optical afterglow data are also shown in Figure 1. We collected additional optical data from the Gamma-ray Coordination Network (GCN), including observations from: SAO RAS 1 m telescope, ZTSh 2.6 m telescope at CrAO observatory, 0.3 m telescope at University of Siena Observatory, 0.28 m f/7 SCT telescope, 0.76 m Katzman Automatic Imaging Telescope (KAIT), MITSuME 50 cm telescope at Akeno, AS-32 telescope at Abastumani observatory, Zeiss 1-m telescope at Simeiz observatory, 0.61 m f/6.5 telescopes at Burke-Gaffney

Observatory, and remote telescope T18 (0.32 m f/8.0 reflector+CCD) of iTelescope. Since the central wavelengths of R and Rc bands together with Clear filters can be treated as the same band, we did not need to calibrate the data with a presumed optical spectral index.

3.1. Prompt Emission

As shown in the upper panel of Figure 1, the prompt emission of GRB 210610B displays three prominent pulses: intense interaction between inhomogeneous outflows creates the first spike, which peaks in the subsequent pulse and decays below detection after the final smaller-amplitude pulse. By combining GBM data from three sodium iodide (NaI) detectors (na, nb, n9) and one bismuth germanate (BGO) detector (b1) with HXMT data from CsI phoswich detectors, we constructed time-resolved spectra for each pulse and time-integrated spectra for the overall prompt emission. All spectra were fitted with a Band function; results are shown in Figure 2 and Table 2 . The fitting indicates no significant evolution across the three pulses in the low-energy photon index ($\hat{\alpha}$), high-energy photon index (β), or peak energy (E_p) related to break energy E_c via the standard relation. Although a more detailed spectral analysis could be performed given the brightness of the prompt emission, such analysis exceeds the scope of this work.

The isotropic energy of the prompt emission can be estimated as:

$$E_{\gamma,\mathrm{iso}} = 4\pi D_L^2 S_\gamma k,$$

where D_L is the luminosity distance, k corrects the observed γ-ray energy to a broader bandpass (e.g., 1–10^4 keV in the rest frame) using the observed GRB spectrum, and S_γ is the γ-ray fluence. For GRB 210610B at redshift z = 1.1345, we calculate D_L = 2.38 × 10^{28} cm. Integrating fluxes from T_0 + 10 s to T_0 + 65 s in 8–1000 keV yields S_γ = (1.37 ± 0.19) × 10^{-4} erg cm^{-2}, giving E_γ,iso = (5.55 ± 0.78) × 10^{53} erg. The isotropic energy and peak energy of GRB 210610B obey the Amati relation from Wang et al. (2018), as shown in Figure 3 [Figure 3: see original paper].

3.2. Afterglow Emission

To investigate GRB 210610B's afterglow properties, we performed comprehensive temporal and spectral analyses. Single power-law (SPL) and smoothly broken power-law (BPL) functions are commonly used to describe afterglow light curve evolution. The SPL is expressed as:

$$F(t) = F_{01} t^{-\alpha},$$

where F_{01} is the flux normalization and α is the decay slope.

The BPL function is expressed as:

$$F(t) = F_{02} \left[\left(\frac{t}{t_b} \right)^{\omega\alpha_1} + \left(\frac{t}{t_b} \right)^{\omega\alpha_2} \right]^{-1/\omega},$$

where F_{02} is the normalization factor, α_1 and α_2 are decay indices before and after break time t_b, and ω represents the break sharpness.

Theoretically, the afterglow model has two cases depending on when energy injection ends relative to when $1/\Gamma$ (the inverse of the jet's bulk Lorentz factor) drops below the jet opening angle _j. If injection ends before this transition, "normal decay" occurs; otherwise, continuous injection produces shallower post-jet-break decay. For flexibility, a smooth triple power-law (STPL) function can be used:

$$F(t) = F_{03} \left[\left(\frac{t}{t_{b,1}} \right)^{\omega_1\alpha_1} + \left(\frac{t}{t_{b,1}} \right)^{\omega_1\alpha_2} \right]^{-1/\omega_1} \left[1 + \left(\frac{t}{t_{b,2}} \right)^{\omega_2(\alpha_2-\alpha_3)} \right]^{-1/\omega_2},$$

where ω_2 is the sharpness of the second break (t_b,$_2$) and α_3 is the third decay index.

As shown in Figure 4 [Figure 4: see original paper], optical photometry began 1682 s after explosion. The R-band light curve initially shows power-law decay until t 3 × 10^3 s, then exhibits a long-lived bump (plateau) followed by a power-law decay tail. We therefore adopt an STPL function to fit the R-band light curve. Most X-ray and optical light curve breaks are well-fit with $\omega = 3$, consistent with other empirical models. In our fitting, the sharpness parameter ω (ω_2) is fixed at 3. Results are presented in Figure 4 and Table 3 .

Our fits show the long-lived R-band bump has α_R,$_1$ = −0.30 ± 0.02 (again F t$^-\alpha$ $^-\beta$). After peaking at 14125 s, it transitions to power-law decay with α_R,$_2$ = 0.87 ± 0.06, followed by an even steeper decay with α_R,$_3$ = 1.77 ± 0.07.

The X-ray light curve is fitted with the STPL function while masking an excess from 400 s to 7000 s. The early X-ray flux decays continuously with α_X,$_1$ = 2.06 ± 0.05, followed by a potential plateau with α_X,$_2$ = −0.30 (fixed) around 5 × 10^3 s. After break time t_b,$_2$, the light curve decays with index α_X,$_2$ = 1.81 ± 0.09. Due to sparse data in the 7 × 10^3–4 × 10^4 s phase, the break time is poorly constrained.

Early-time X-ray plateaus followed by steep decay generally involve magnetar spin-down. The magnetic dipole torque luminosity is:

$$L(t) = \frac{L_0}{(1 + t/T)^n},$$

where L_0 $B^2R^6\Omega_0{}^4/(6c^3)$ 10^{49} $B_{15}{}^2$ $P_{0,\,3}{}^{-4}$ $R_6{}^6$ erg s^{-1} is the initial luminosity corresponding to initial angular velocity Ω_0, T τ(1+z) is the spin-down timescale, $\tau = 3c^3I/(B^2R^6\Omega_0{}^2)$ 2.05 × 10^3 $B_{15}{}^{-2}$ P_0, $_3{}^2$ I_{45} $R_6{}^{-6}$ s is the characteristic spin-down time, and n is the braking index. Assuming the X-ray emission efficiency of spin-down luminosity is _X, we have:

$$L_{X,\mathrm{iso}} = \eta_X L(t) = \frac{L_{X,\mathrm{iso},0}}{(1+t/T)^n},$$

where L_X,iso,$_0$ = _X L$_0$, T = τ(1+z), and n 3. Therefore, the early X-ray plateau and subsequent steep decay can be fitted with:

$$F_X(t) = \frac{L_{X,\mathrm{iso},0}}{4\pi D_L^2(1+z)^{1-\alpha}} \left(1+\frac{t}{T}\right)^{-n},$$

where z is redshift and D_L is luminosity distance. Fixing $\alpha = 2.05$ from above and $\log_{10}$ L_X,iso,$_0$ = 48.29, the obtained parameters are: $\log_{10}$ L_X,iso,$_0$ = 48.29, $\log_{10}$ T = 3.45, and n = 3.04.

Before spectral fitting, we corrected X-ray and optical data for Galactic and intrinsic absorption. Galactic absorption toward the burst (N_H = 3.94 × 10^{20} cm^{-2}) is adopted from the UK Swift Science Data Center at the University of Leicester. Intrinsic absorption was fixed to N_H estimated from late-time (40–1000 ks) XRT spectral analysis. Galactic extinction correction used Schlegel & Finkbeiner (2011) values for the burst direction. Host galaxy extinction is assumed to follow Small Magellanic Cloud (SMC) extinction curves with R_V = 2.93.

We used Xspec to fit X-ray spectra and extrapolate unabsorbed power-law spectra to the optical band. Seven epochs of time-resolved spectra were extracted, though some photon indices are poorly constrained due to sparse data. Spectral fitting results are shown in Table 4 and Figure 5 [Figure 5: see original paper]. We adopt Γ_γ = 1.80 as the average value, consistent with late-time X-ray spectral fitting (40–1000 ks).

The spectral index β = Γ_γ − 1 = 0.80 can be used with the α–β closure relations of the fireball external shock model to calculate predicted temporal indices: α = (3β+1)/2 = 1.7 for constant-density ISM and α = (3β−1)/2 = 0.7 for wind-like media. Our fitting results (α_X,$_2$ 1.81 and α_R,$_3$ 1.77) suggest a wind-like medium with observed frequency in the _m < < _c spectral regime.

The long-lived optical plateau may also result from energy injection, testable via closure relations. Assuming a long-lasting central engine with L(t) t⁻q, the temporal index becomes α = (2+q) + (p−2)(1+q)/2 for wind-like media. If the injected energy originates from a millisecond magnetar, q = 0 is required before characteristic timescale T and q = −2 after T, returning to self-similar behavior according to the spin-down law. This yields a shallow decay slope of 0.8, in excellent agreement with our fitting result α_R,$_2$ 0.88 in wind-like media, suggesting the magnetar may indeed be the central engine.

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4. Modeling: The Later-launched Ejecta Catching up with the External Shock

A general density profile with stratification parameter s (where s = 0 and s = 2 correspond to ISM and wind cases) can be written as n(r) = Ar^{-} , where A = M/(4πm_p v_w) for wind media with mass-loss rate M and wind velocity v_w. The external forward shock model provides a robust framework for explaining afterglow behavior. We adopt the standard external shock model from Sari et al. (1998).

The dynamical evolution is calculated following Huang et al. (1999) using four coupled first-order differential equations:

$$\frac{dR}{dt} = \beta c,$$

$$\frac{dm}{dt} = 4\pi R^2 n(R) m_p \beta c,$$

$$\frac{d\Gamma}{dt} = \frac{1}{M_{ej} + m}\left[\frac{dE_{inj}}{dt_{obs}} - (\Gamma^2 - 1)\frac{dm}{dt} - (\Gamma - 1)\frac{dM_{ej}}{dt}\right],$$

$$\frac{dU'}{dt} = \frac{dE_{inj}}{dt_{obs}} - \frac{U'}{\Gamma}\frac{d\Gamma}{dt} - \frac{U'}{R^2}\frac{dR}{dt} - \frac{dE_{rad}}{dt_{obs}},$$

where βc is the bulk fireball velocity, m is the rest mass of swept-up medium, U' is internal energy, is shock efficiency (= 1 for radiative, = 0 for adiabatic expansion), and M_{ej} is the initial ejecta mass. Sideways expansion of the relativistic jet is ignored as it doesn't significantly affect flux until Γ drops below 2.

Free parameters include: isotropic kinetic energy E_K,iso, microphysical parameters _e and _B, initial Lorentz factor Γ_0, wind parameter A_*, injection luminosity L_{inj},$_0$, injection start/end times t_s and t_e, and parameter δ. The electron distribution power-law index is fixed at p = 2β + 1 = 2.60. With no obvious jet break, we roughly constrain _j > 5° due to the lack of a jet break feature.

An MCMC method was used to fit the model by searching parameter space extensively. The emcee module handled MCMC simulations with 90 walkers. Parameter ranges were: $\log_{10}$ _B [−5.00, −3.00], $\log_{10}$ _e [−1.00, 0.00], $\log_{10}$ E_K,iso [53.00, 54.00] erg, $\log_{10}$ Γ_0 [2.00, 3.00], $\log_{10}$ A_* [−2.00, −1.00], $\log_{10}$ L_{inj},$_0$ [50.0, 51.0] erg s^{-1}, $\log_{10}$ t_s [3.20, 3.90] s, $\log_{10}$ t_e [4.00, 5.50] s, and δ [1.0, 2.0].

The MCMC results provide best-fitting parameters: $\log_{10}$ _B = −4.33 ± 0.11, $\log_{10}$ _e = −0.81 ± 0.06, $\log_{10}$(E_K,iso/erg) = 53.64 ± 0.04, $\log_{10}$ Γ_0 = 2.92 ± 0.02, $\log_{10}$ A_* = −0.99 ± 0.07, $\log_{10}$(L_{inj},$_0$/erg s^{-1}) = 50.55 ± 0.07, and δ = 1.68 ± 0.23. Figure 1 shows our fitted light curve, and Figure 6 [Figure 6: see original paper] displays parameter sampling results. All parameters lie in reasonable ranges compared to large GRB samples. Notably, A_* 0.10 is smaller than the standard value of 1, indicating a sparse surrounding density. This sparse medium cannot effectively decelerate the blast wave, explaining the absence of a jet break before 11.6 days. The jet break time in stellar wind environments is given by t_{jet} 0.6(1+z)E$_{53}$$^{-1\ 3}$ $_{0}$$^{8\ 3}$ days, where E$_{53}$ includes both isotropic γ-ray energy and kinetic energy in units of 10^{53} erg, and $_{0}$ is the jet opening angle in radians. This constrains _j 3°, consistent with recent studies though smaller than earlier estimates.

Yi et al. (2022) analyzed 174 GRBs with X-ray plateaus and 106 with X-ray flares, finding Gaussian distributions of logarithmic energy ratios with medians −0.96 and −1.39, respectively. They argue that plateaus and flares share a common physical origin but manifest differently due to varying conditions and radiation mechanisms. Some studies suggest mass-loaded jets (“dirty fireballs”) with initial Lorentz factors Γ_{init} 100 could produce lower-energy peaks appearing as prompt X-ray emission. Making the aggressive assumption that a similar scenario applies to the early X-ray plateau, the Lorentz factor of the launched ejecta in GRB 210610B would not be too large.

Based on t_s, the time lag between photon formation at the internal dissipation radius (R_{dis}) and injection radius (R_{inj}), we deduce the average Lorentz factor of the later-launched ejecta is Γ_2 51. This is a lower limit because continuous ejection is implied; the later ejecta needs a larger Lorentz factor to catch the blast wave at R_{inj}.

The GRB radiative efficiency _γ = E_γ,iso/(E_γ,iso + E_K,iso) = 56.0% reflects internal dissipation efficiency within the first ejecta. For the later ejecta, internal dissipation efficiency is _X L_{XT}/(L_{XT} + E_{inj}), where injected isotropic energy is obtained by integrating dE_{inj}/dt_{obs} from t_s to t_e:

$$E_{inj} = \int_{t_s}^{t_e} \frac{dE_{inj}}{dt_{obs}} dt_{obs} = 2.0 \times 10^{54} \text{ erg},$$

yielding _X 0.1%.

Plateau parameters after beaming correction are:

$$L_{X,0} = \frac{L_{X,\mathrm{iso},0}}{f_b}, \quad T = \frac{\tau}{1+z},$$

where f_b = 1 − cos _j is the beaming correction factor. Millisecond magnetar parameters can be inferred using standard values I$_{45}$ 1 and R$_{6}$ 1, giving initial spin period P 2.6 ms and surface polar cap magnetic field strength B 3.2 × 10^{15} G, consistent with the GRB magnetar population.

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5. Conclusions and Discussion

GRB 210610B was detected by Swift/BAT, Fermi/GBM, and HXMT/HE, showing multi-pulse profiles. Its afterglow light curves exhibit distinct plateaus from broadband follow-up observations. Our main conclusions from temporal and spectral analyses are:

1. **Prompt Emission**: Band function fits to time-resolved and time-integrated spectra yield parameters ($\hat{\alpha} = -0.47 \pm 0.05$, $\beta = -2.73 \pm 0.22$, E_p = 305 ± 24 keV) that give isotropic γ-ray energy E_γ,iso = $(5.55 \pm 0.78) \times 10^{53}$ erg in the 1–10000 keV band (rest frame), which falls on the long GRB Amati relation.
2. **Afterglow Emission**: X-ray-to-optical SEDs show no obvious evolution, with average photon index Γ_γ 1.80. The early X-ray light curve exhibits a plateau followed by steep decay that fits well with F_X(t) $(1 + t/T)^{-n}$, giving n 3.04.
3. **Modeling**: Joint temporal and spectral fits of multiwavelength light curves indicate an external shock propagating in a stellar wind medium, with energy injection describing afterglow behavior. Best parameters are: log$_{10}$ _B = −4.33, log$_{10}$ _e = −0.81, log$_{10}$(E_K,iso/erg) = 53.64, log$_{10}$ Γ_0 = 2.92, log$_{10}$ A_* = −0.99, log$_{10}$(L_{inj},$_0$/erg s^{-1}) = 50.55, and δ = 1.68.

We did not perform deep spectral analysis of GRB 210610B. Chen et al. (2022) found that 76% of spectra require an additional thermal component for better fits, suggesting the Poynting flux component may be important beyond the hot fireball component. Our afterglow-phase results similarly suggest a magnetar central engine, consistent with Chen et al. (2022).

Incorporating early R-band data (before 6 ks) into our model yields good fits, suggesting early optical emission is primarily from the external forward shock with _a < _R < _m. Figure 7 [Figure 7: see original paper] traces synchrotron parameters _m and _c over time. The light curve changes smoothly due to curvature effects as _R crosses _m. For early blast wave evolution, fast cooling and synchrotron self-absorption may be significant; multiwavelength optical follow-up could clarify this complex situation.

Acknowledgments

We thank the anonymous referee for useful comments that improved this paper. This work was funded by the National Natural Science Foundation of China (Nos. 12373042, U1938201, 12273005, 12133003) and the Bagui Scholars Programme (WXG). We also acknowledge support from the China Space Station Telescope (CSST). We are grateful for public GRB data from Fermi/GBM, Swift, and HXMT.

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