

Complex Multi-flares of GRB 250129A: evidence of Successive Shock Interactions

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ABSTRACT

Context. Most long gamma-ray bursts (GRBs) exhibit afterglows broadly consistent with external forward-shock emission, typically described by smooth broken power-law decays in the multi-band light curve. However, a minority of well-sampled GRBs deviate from this behavior, as the GRB we are investigating in this article, GRB 250129A. The latter shows late-time rebrightenings in the X-ray and optical wavelengths or rebrightenings often attributed to energy injection from prolonged central engine activity or refreshed shocks due to delayed collisions between relativistic ejecta shells.

Aims. We aim to investigate the physical origin of the multiple X-ray and optical flaring episodes observed in GRB 250129A. Several leading scenarios are considered, including interactions between multiple shells, energy injection from the central engine, the roles of the forward and reverse shocks into the interstellar medium, and the role of the density jump of the circumburst medium.

Methods. We conduct comprehensive temporal and spectral multi-band analyses of GRB 250129A, exhibiting multiple fast optical rebrightening episodes from the X-rays to the near infrared band. The physical processes at play in the multi-wavelength afterglow light curves are being investigated using several methods, ranging from empirical fitting to Bayesian inference. The high-quality monitoring of the flare episodes and the connection between the afterglow and the prompt allow us to test the compatibility of the fireball model, while taking further steps by rejecting or confirming alternative scenarios, as well as determining if additional analyses are necessary to gain a comprehensive understanding of the rebrightenings.

Results. Standard energy injection models produce inconsistent inferred physical parameters across individual rebrightening phases. Hence, it cannot adequately model the observed rebrightening of GRB 250129A. The timing and flux evolution of the rebrightenings are best explained by refreshed shocks arising from delayed collisions between relativistic shells, consistent with evolving outflow dynamics.

Conclusions.

Key words. gamma-ray burst: individual: GRB 250129A – transients: gamma-ray bursts

1. Introduction

Gamma-ray bursts (GRBs) are among the most luminous and violent electromagnetic phenomena observed in the universe (Kumar & Zhang 2015a; Piran 2004). Based on their T_{90} duration over which the central 90% of the gamma-ray fluence is accumulated, they are classified into two categories, short ($T_{90} < 2$ s)

or long ($T_{90} > 2$ s) GRBs (Kouveliotou et al. 1993). A large fraction of long GRBs is suggested to originate from the collapse of massive stars, as confirmed through associations with broad-line Type Ic supernovae (Woosley 1993; MacFadyen & Woosley 1999; Woosley & Heger 2012; Hussenot-Desenonges et al. 2024), although a subset may originate from alternative progenitors (Neights et al. 2025; Luo et al. 2023; Rastinejad et al. 2022). Conversely, short GRBs emerge from the merger of compact objects (Paczynski 1986; Eichler et al. 1989; Paczyński 1991; Narayan et al. 1992), as evidenced by their joint detections

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of associated kilonovae and gravitational waves (Abbott et al. 2017; Cano et al. 2017).

One of the most favored explanations for GRBs is the *fireball model* (Piran 1999a; Kumar & Zhang 2015b; Waxman & Piran 1994; Meszaros & Rees 1993), in which the prompt gamma-ray emission arises from energy dissipation within a narrow relativistic jet due to internal shocks produced by collisions between discrete shells with different velocities. The jet is decelerated by its interaction with the external medium, which drives an external forward shock and produces the long-lasting and broadband (radio to X-rays) synchrotron afterglow emission. Post-deceleration, the afterglow emission typically declines over time as a power law in the X-ray and optical bands when both are produced by the same power-law segment of the synchrotron spectrum. Although fireball dynamics are often approximated as spherical at early times, the outflow is in fact collimated into a jet of half-opening angle θ_j . As the blast wave decelerates, the relativistic beaming angle (with size $1/\Gamma$) increases and eventually exceeds θ_j , causing the jet edge to become visible and allowing lateral expansion to set in. This leads to the characteristic steepening of the afterglow light curve known as the jet break (Rhoads 1999; Sari et al. 1999).

The light curve of GRB afterglows is expected to follow a smooth temporal evolution; however, intense, rapid rebrightenings (or flares), gradual ones lasting over minutes to days, and other irregularities in the multi-band afterglow light curve are often revealed in a fraction of high-cadence GRBs with well-sampled multi-band observations (Evans et al. 2009; Nousek et al. 2006a; Kumar & Zhang 2015c; de Ugarte Postigo, A. et al. 2018; Busmann et al. 2025). Between 20 and 30% of long GRBs exhibit optical rebrightenings in their afterglow (e.g., Li et al. 2012; Becerra et al. 2023).

One possible explanation includes energy injection into the blast wave due to the expulsion of multiple shells by the central engine that later collide and produce a rapid brightening of the afterglow (Kumar & Piran 2000a; Panaitescu et al. 1998; Rees & Meszaros 1998; Sari & Meszaros 2000a; Zhang & Mészáros 2002; Uhm et al. 2012; Laskar et al. 2015a; Fraija et al. 2022; Moss et al. 2023). The GRB central engine is expected to be erratic, and the expulsion of late shells may be associated with fall-back of material onto the central engine (MacFadyen et al. 2001). Late-time energy injection has been used to explain observed plateaus and rebrightenings in a substantial number of GRBs (Laskar et al. 2015a; Nousek et al. 2006b; Yu et al. 2007; Margutti et al. 2010).

Alternatively, energy can be added to the blast wave gradually and continuously. This can occur when the ejecta has a radial velocity gradient (Granot & Kumar 2006; Zhang et al. 2006; van Eerten 2018; Ryan et al. 2020), with progressively slower moving inner shells trailing behind the faster moving outer shell, or if the central engine is a magnetar that injects energy continuously into the blast wave via a magneto-hydrodynamic (MHD) pulsar-type wind (Dai & Lu 1998; Zhang & Mészáros 2002, 2001; Geng et al. 2016). In both scenarios, the afterglow light curve shows an achromatic bump or rebrightening as the energy is injected, with the post-injection light curve following the same temporal decay as that of the pre-injection one in the absence of spectral break passage. Multiple rebrightening episodes are not possible in this scenario.

Such multiple episodes have been explained by having an asymmetric structured jet, where different azimuthal jet components, with distinct energies and Lorentz factors, sequentially dominate the afterglow emission, producing multiple peaks (Li et al. 2024). Another possible explanation includes a non-uniform

circumburst environment in which the blast wave encounters density enhancements that could lead to rebrightenings (Wang & Loeb 2000a; Dai & Lu 2002; Uhm & Zhang 2014). These density structures may be organized as spherical shells formed by unstable wind episodes of the progenitor or clumpy remnant of a previous supernova explosion, a scenario consistent with constraints from multiwavelength imaging and spectroscopy (Huang et al. 2006; Lazzati et al. 2002; Wang & Loeb 2000b). However, analytic calculations (Nakar & Granot 2007) and numerical simulations (van Eerten et al. 2009) show that even large density enhancements will only produce a mild rebrightening in the light curve.

In this paper, we present multi-waveband observations of GRB 250129A that was detected by the *Swift*/BAT instrument on the *Neil Gehrels Swift Observatory* at $T_0 = 2025$ January 29 04:45:09 UTC (Beardmore et al. 2025) (trigger num: 1285812, SNR in the image trigger of 10.13, duration of the trigger: 64s in the 15 - 50 KeV energy band). It was simultaneously detected by *Konus-Wind* from T_0-66 s to T_0+208 s in the [20 - 400] keV with detection significance above 6σ (Frederiks et al. 2025). The GRB was classified as a long burst with a duration of $T_{90} = 262.25 \pm 23.71$ seconds as determined by the online analysis in the 15-350 keV band. *Swift* initiated an automatic slew and performed follow-up observations with *Swift*/XRT and the Ultra-Violet and Optical Telescope onboard *Swift* (UVOT, see Roming et al. 2005) (Siegel et al. 2025) commencing at $T_0 + 158.6$ s. Both X-ray and optical counterparts were found: the first follow-up revealed an uncatalogued X-ray source located 54 arcseconds from the BAT position (Beardmore et al. 2025) and a candidate optical afterglow with a magnitude of 17.88, positioned within 2.7 arcseconds of the XRT localization, in the white filter (Beardmore et al. 2025).

Various follow-up observations were initiated rapidly, beginning as early as 1.9 minutes after T_0 , even while the prompt emission was ongoing and continued over several weeks. These efforts involved more than 40 ground-based telescopes and instruments. For instance, early optical imaging was conducted by the OHP-T193 cm telescope, 30 minutes after the *Swift*/BAT trigger (Schneider et al. 2025b) and the Las Cumbres Observatory Global Telescope (Ghosh et al. 2025) 1.17 hr post-trigger; while extended monitoring was carried out by the 2m robotic Liverpool Telescope and the SAO RAS 1-m telescope, ~ 24.1 hr and ~ 43.298 hr after the trigger, respectively (Bochenek & Perley 2025; Moskvitin et al. 2025) (see all GCN reports). Observations were also conducted by the COLIBRI telescope (Watson et al. 2025a; Akl et al. 2025a; Watson et al. 2025b), as well as the Global Rapid Advanced Network Devoted to Multi-messenger Addicts (GRANDMA) (Antier et al. 2020) and its citizen science program, Kilonova-Catcher (KNC) (Antier et al. 2025; Akl et al. 2025b) (see the GRB250129A Skyportal Public Page to retrieve results submitted by various teams. Note that these are uncorrected for the extinctions.

The first observations showed a steep optical and X-ray rebrightening within the first day, a feature that cannot be accounted for by a standard fireball afterglow model (Piran 1999b; Zhang et al. 2006), and thus motivated long-term follow-up that revealed additional rebrightening episodes. GRB250129A redshift was also measured at $z = 2.151$ from VLT/X-shooter at $T - T_0 = 1.315$ hours (Schneider et al. 2025a): the observations revealed Ly α absorption at $\sim 3830\text{\AA}$, along with absorption lines from ions such as SiII, CIV, and FeII. This redshift was later confirmed by the Nordic Optical Telescope (NOT)'s (Izzo et al. 2025), and the MISTRAL spectro-imager at Observatoire de

haute provence (Schneider et al. 2025c).

We performed a multi-stage modeling analysis of the GRB 250129A afterglow to probe the physical origin of its rebrightening episodes, investigating mechanisms linked to central energy reactivation. We focus on scenarios involving energy injection into the forward shock and a series of refreshed shocks produced by collisions between shells with different bulk Lorentz factors launched during the prompt phase.

The paper is structured as follows. In §2, we present the observational data set, including the prompt emission and multi-wavelength afterglow data from gamma-ray, X-ray, optical, and UV observations. In §3, we perform an analysis of the dust environment and the possible host galaxy. In §4, we present the theoretical modeling and physical interpretation of the event based on various jet structure scenarios. Finally, we summarize our conclusions in §5.

2. Observational dataset

2.1. Prompt Observations

Gamma-Ray – We analyzed the temporal and spectral characteristics of the GRB prompt emission observed by *Swift*/BAT. Mask-weighted light curves (binned to a signal-to-noise ratio of 5) and spectra were constructed using *batbinevt*. We defined four burst intervals based on the edges obtained from the Bayesian block algorithm (Scargle et al. 2013) and the rise and decay slopes of the pulses, as shown in the top panel of Figure 1.

Time-resolved spectra were extracted for the four intervals, and the spectral models were selected between a single power-law (SPL) and a cutoff power-law (CPL) using Bayesian Information Criterion (BIC) tests, requiring an improvement of $\Delta\text{BIC} = 4$. Intervals 1, 2, and 4 are best fitted by SPL models, while Interval 3 is best fitted by a CPL model with $\alpha = -1.20^{+0.25}_{-0.24}$ and $E_0 = 42^{+17}_{-10}$ keV, which is consistent to the result reported by *Konus-Wind* (Frederiks et al. 2025). The time-resolved spectra as well as corresponding intervals are shown in Figure 2. Based on the best-fit spectral models, the photon counts were subsequently converted to the flux density at 10 keV, as shown in Figure 1.

Accounting for the cosmological k -correction (Bloom et al. 2001), we calculate an isotropic-equivalent energy of $E_{\text{iso},\gamma} = (1.35 \pm 0.12) \times 10^{53}$ erg by summing the fluence over the four intervals.

Optical Observations During the Prompt Emission – The Telescopes à Action Rapide pour les Objets Transitoires (TAROT)¹ associated with the GRANDMA collaboration started observing the GRB about 106 seconds after T_0 in drift mode and without filter (e.g. the tracking of the hour-angle motor was adapted to a drift of 0.30 pixel/s), enabling a record of the flux during 60s without dead time (Klotz et al. 2006). This sequence, covering the prompt emission during about 70 seconds, is shown in Figure 1.

2.2. X-ray Afterglow

Light curve – We retrieved the XRT unabsorbed flux density light curves resampled for the 10 keV band from the Burst Analyser². We rebinned the light curve by grouping data points

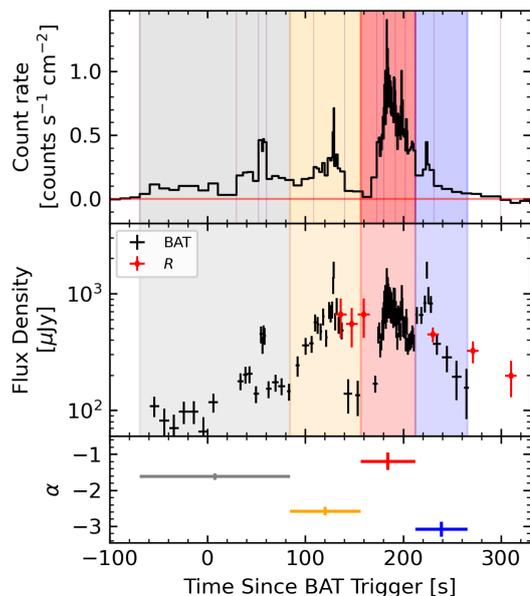


Fig. 1. Top: *Swift*/BAT mask-weighted count-rate light curve with Bayesian block edges. Middle: *Swift*/BAT (10 keV) and TAROT R-band flux density light curves. Bottom: Best-fit spectral indices.

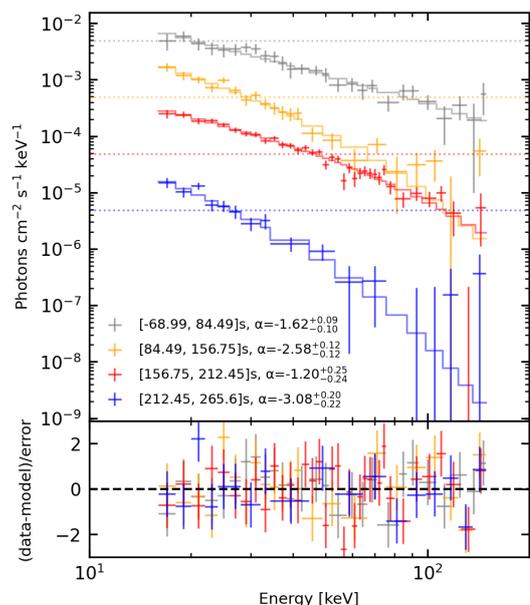


Fig. 2. BAT 15–150 keV time-resolved spectra and best-fit models for GRB 250129A. For clarity, the fluxes of successive intervals are scaled by a constant factor of 0.1 relative to the previous interval; the horizontal dashed lines indicate the reference flux levels of the first interval. The fit results are reported with 90% confidence intervals. "0" corresponds to the time of the trigger T_0 .

into 16 manually defined, non-contiguous clusters based on temporal proximity to improve the signal-to-noise ratio while preserving the time evolution. Among these, 4 bins contained clusters of 2–5 closely spaced observations, while the remaining bins contained a single point each. For each bin, we computed the mean magnitude and standard deviation. We then converted the flux density from 10 keV to 2 keV (see Appendix C), to ensure our analysis is grounded in the energy range where *Swift*-XRT

¹ <http://tarot.obs-hp.fr/>

² https://www.swift.ac.uk/burst_analyser/01285812/

is most sensitive. The light curve can be seen in Figure 5, and all the data are available in Skyportal and in Table D.2 of the Appendix.

Time resolved spectra – We extracted the spectral characteristics in the [0.3–10 keV] range of *Swift*-XRT data in various epochs (see Figure 3). The data reduction and spectral analysis were conducted in the same approach for all the epochs using *HEASoft* v6.34, and processed using the *XRT* tool *xrtpipeline* (v0.13.7). The spectra were fitted with an absorbed power-law model, leaving only the photon index (Γ) and the normalization as free parameters, with the galactic column density ($N_H = 2.4 \times 10^{20} \text{ cm}^{-2}$) fixed³. Spectral modeling and parameter estimation were performed using standard processing (See Appendix C).

We first investigated potential spectral evolution within the first day following the discovery from 2025-01-29T05:04:40 to 2025-01-29T18:49:13, as the low count rate after the first day prevented the fitting for properties such as the photon index. The best-fit photon indices for the three source spectra within the first day shared the same characteristics with the photon index $\Gamma = 1.99 \pm 0.23$, $\Gamma = 2.15 \pm 0.15$, and $\Gamma = 1.87 \pm 0.18$, respectively. We then analyzed one epoch more carefully, which corresponds to high variation in optical. We split the period [0.061–0.197] post T0 at $T = 0.061$, which coincides with a transition in the optical light curve from a rising to a decaying phase. Separate spectral fits were performed for each using the same method outlined in Appendix C. The resulting photon indices were $\Gamma = 2.22 \pm 0.18$ for the rising phase and $\Gamma = 2.11 \pm 0.34$ for the decaying phase. While the values differ slightly, the uncertainties overlap significantly, indicating no statistically significant spectral evolution during this period. This is further discussed by fitting the spectral energy distribution (SED), as detailed in ??.

2.3. UVOIR Afterglow

Space – We performed aperture photometry in *UVW1*, *UVW2*, *UVM2* (ultraviolet), and *U*, *B*, *V* (optical) to extract the *Swift*/UVOT light curve using a 5''-radius circular source region and a 15''-radius background region away from the source. For individual exposures, we employed the *uvotmaghist* task. In addition, we selectively co-added exposures that were close in time within a range of a couple of minutes in the same band, identified based on their temporal distribution on a log-time scale plot. These subsets were summed using *uvotimsum*, and photometry was then performed using *uvotsource*. This approach allowed us to preserve time resolution where needed and improve signal-to-noise ratio, as well as decrease uncertainty and error, particularly with the exposures that were clustered closely in time.

Very early-time exposures initially excluded by *uvotmaghist* due to failed aspect correction (i.e., *ASPCORR* keyword set to *NONE*) were manually corrected using *uvotaspcorr* to allow for their inclusion. The initial *V*-band settling image was also examined for detector ramp-up effects. To assess its reliability, we compared the photometry of field stars in the settling image with that from later stacked *V*-band exposures. Additionally, we considered non-detection when the signal-to-noise is under 2, which is typically associated with contamination from known internal dust regions within the telescope. All the UVOT data are available in Table D.3 and shown in Figure 5.

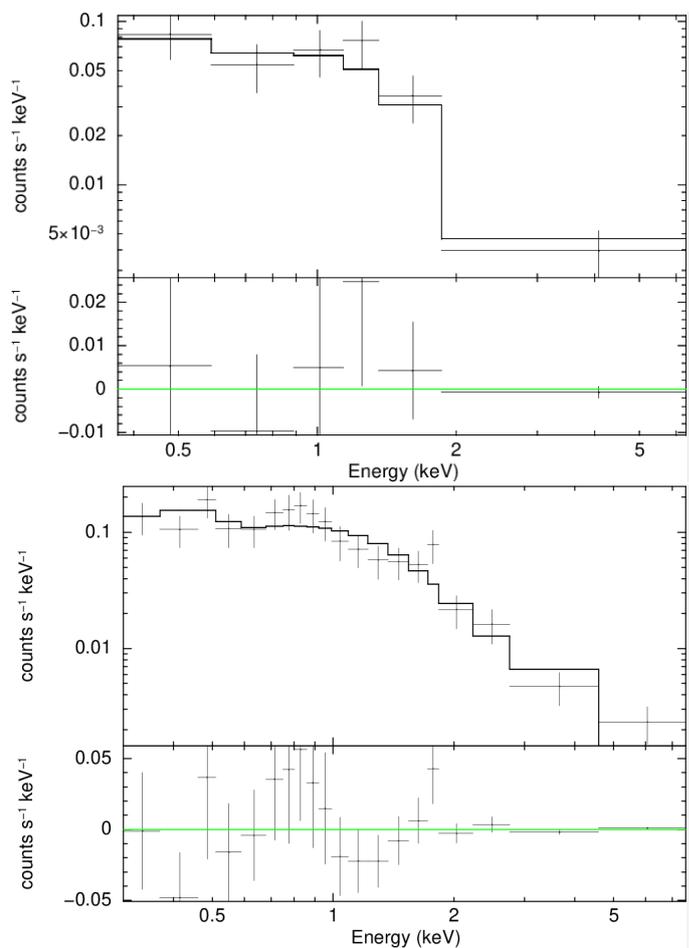


Fig. 3. X-ray spectra fitted with a power-law (PL) model. **Top panel:** Spectrum from the decay interval of observation ID 01285812001, corresponding to $T - T_0 = 0.1355$ to 0.1969 days. **Bottom panel:** Spectrum from the rise interval of the same observation, spanning $T - T_0 = 0.061$ to 0.1355 days.

Ground – The processing of all optical observations of the 30 different instruments at play followed the same methodologies to maintain consistency and data quality. The pre-processing after data acquisition started with bias and dark subtraction, as well as flat-field correction according to each telescope’s specifics. We then manually masked areas within each image with visible imaging artifacts or areas that were not entirely corrected during pre-processing (especially at the edges). We verified or derived astrometric solutions using the *astrometry.net* service (Lang et al. 2010), on either individual images or stacked images. We performed dynamical image stacking using the *SWarp* software (Bertin 2010) to retain high temporal resolution and a signal-to-noise ratio above 3 at the location of the transient.

Forced photometry of all the stacked images (e.g., ~ 290 images) was performed at the transient position (e.g., RA, Dec: 198.676728, 5.030631) using *STDPipe* (Karpov 2021; Karpov 2025), a home-made Python-based set of codes for performing astrometry, photometry, and transient detection tasks on optical images, originally created as part of the GRANDMA Collaboration. We utilized the associated web interface *STDWeb*⁴ to conduct our photometry and seek for anomalies that need further adjustments (e.g., high background noise, calibration issues, etc). Catalogs for the photometric calibration were chosen based

³ https://www.swift.ac.uk/xrt_spectra/01285812/

⁴ Accessible at <http://stdweb.favor2.info>

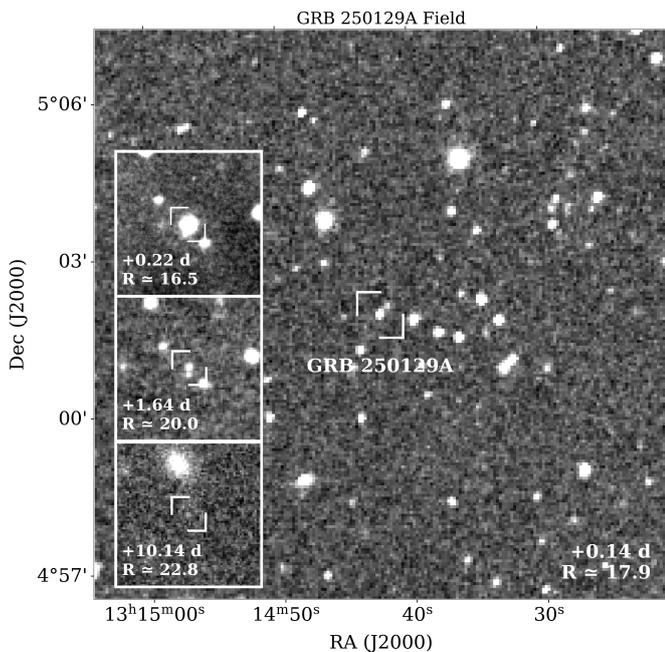


Fig. 4. TAROT-TCH telescope image of GRB 250129A taken at $T - T_0 = 0.14$ d. The insets show the zoomed-in region of three images from the KAIT, Abastumani-T70, and Euler telescopes centered on the GRB location, taken at phases of $T - T_0 = 0.22$, $T - T_0 = 1.64$, and $T - T_0 = 10.14$ d, respectively, relative to the *Swift* GRB trigger (MJD 60704.198).

on the filters used to acquire the images. Instrumental magnitudes were calibrated using the Gaia DR3 Synthetic Photometry Catalog (Gaia Collaboration et al. 2023) and Pan-STARRS Data Release 1 catalog (Chambers et al. 2016) for images obtained in filters close to the Johnson-Cousins filter system (U , B , V , R_c , I_c) and Sloan filters (g , r , i , z), respectively. Images obtained using non-standard filters (not part of the Johnson-Cousins or Sloan systems) were calibrated using the filter and catalogue, which minimized the color term⁵ to below 0.1. Particularly, unfiltered images are challenging since they cover the full wavelength range.

Specific treatment of several images was required to correctly calibrate them using standard catalogs. For example, a first non-linear color term was needed to adjust the data of the early afterglow ($T - T_0 < 0.2$ day): the color term estimation had to be modified into a parabolic color term, which was then used to fit both datasets from the TAROT/TCH and FRAM-Auger telescopes. Specifically, the correction for the color we obtained is $B - V = 1.46$ ($\sim g - r = 1.27$). Hence, the color term was applied to TAROT/TCH as $[R + 0.44(B - V) - 0.29(B - V)^2]$ and to FRAM-Auger data as $[R + 0.06(B - V)]$. As shown in Figure 5, the results are compatible in the R -band. We additionally added data from Skynet telescopes in the B -, V -, R -, and I -bands, and we applied a joint color correction of $(B - V) = 0.4$ to Skynet, TAROT/TCH, and FRAM-Auger to minimize the offsets introduced by the distinct filter responses of the telescopes. This correction indicated that the transient exhibited a relatively blue color of $(B - V) = 0.4$ during the early-time window, thereby superseding our earlier interpretation that the transient was red at early times.

⁵ For example, $g-r$ for Sloan-like filters in order to assess how much the individual photometric system of the image deviates from the catalog one

At later times, from $0.2 < T - T_0 < 1$ days, the analysis of KAIT data taken without a filter was challenging due to poor background quality and high noise levels in certain images; no color term corrections were applied as their inclusion led to further instability in the fit. To mitigate these issues, the number of free parameters was minimized: the background mesh size, or the size of the grid cells used for global background estimation, was reduced to 32 pixels, with a constant zero-point, and a reduced annulus size was constrained to apertures of 2 and 4 FWHM for the sky inner and outer annuli, respectively.

Finally, when the afterglow reached a magnitude above 21.5 magnitude, we subtracted a template image from the Legacy DESI Survey Data Release 10⁶ to isolate the flux contribution using High Order Transform of Psf and a template subtraction code HOTPANTS (Becker 2015) algorithm for image subtraction.

Besides, observations included one infrared J-band image obtained by the Pic Du Midi telescope; however, this data point was not used in the offline analysis as it only included one upper limit.

3. Environment

3.1. Host galaxy line-of-sight extinction

The line-of-sight host galaxy dust extinction has been estimated by creating an X-ray-to-optical spectral energy distribution (SED) using *Swift*/XRT and optical data ($g'r'i'z'$), corrected from the Galactic reddening of $E(B - V) = 0.03$ mag (Schlafly & Finkbeiner 2011b), at a mid-time of $t - t_0 \sim 7.04$ days after the *Swift* trigger, where no further spectral evolution is observed. We note that due to the absence of NIR data to construct the SED, the estimated extinction might be underestimated. Indeed, determining optical extinction becomes more complex without NIR observations, as they are less affected by dust than bluer wavelengths. Moreover, they can also serve as crucial anchors in constraining the intrinsic spectral shape of the afterglow.

Compared to section 2.2, we retrieved the time-sliced X-ray spectrum, covering the 2.22-12.74 days interval, keeping high timing resolution and directly from the automated data products provided by the public *Swift*/XRT archive (Evans et al. 2007). Photometric data in the $g'r'i'z'$ bands from section 2.3 were interpolated to the common reference time of the z' -band (e.g MJD 60711.237) at ~ 7.04 days after the trigger. The SED fit was performed by following a standard routine using the average extinction curves of the Milky Way (MW), Large (LMC), and Small Magellanic (SMC) Clouds (Pei 1992), and the intrinsic X-ray-to-optical spectrum was modeled with a single or broken power-law according to the shape of the afterglow theory (Sari et al. 1998a). The slope of the X-ray wavelengths was assumed to be 0.5 steeper than the spectral slope below the cooling break of the intrinsic spectra, i.e., $\Delta\beta = \beta_X - \beta_o = 0.5$. We fixed the redshift and the Galactic foreground absorption of $N_H^{\text{Gal}} = 2.43 \times 10^{20} \text{ cm}^{-2}$ (HI4PI Collaboration et al. 2016; Willingale et al. 2013).

A simple power law model with the MW extinction curve gives a fit with the parameters $\beta = 1.15^{+0.13}_{-0.04}$, $E(B - V) = 0.05^{+0.12}_{-0.03}$ mag, $N_{H,X} = 0.89^{+7.39}_{-0.62} \times 10^{22} \text{ cm}^{-2}$ ($\chi^2_{\text{MW}}/\text{d.o.f} = 12.12/14$). Additionally, the fitted parameters remain consistent across the other extinction curves, with the Large (LMC) and Small Magellanic Clouds (SMC) yielding statistical similar fits of $\chi^2_{\text{LMC}}/\text{d.o.f} = 12.45/14$ and $\chi^2_{\text{SMC}}/\text{d.o.f} = 12.57/14$ (see Fig. 6).

⁶ www.legacysurvey.org/dr10

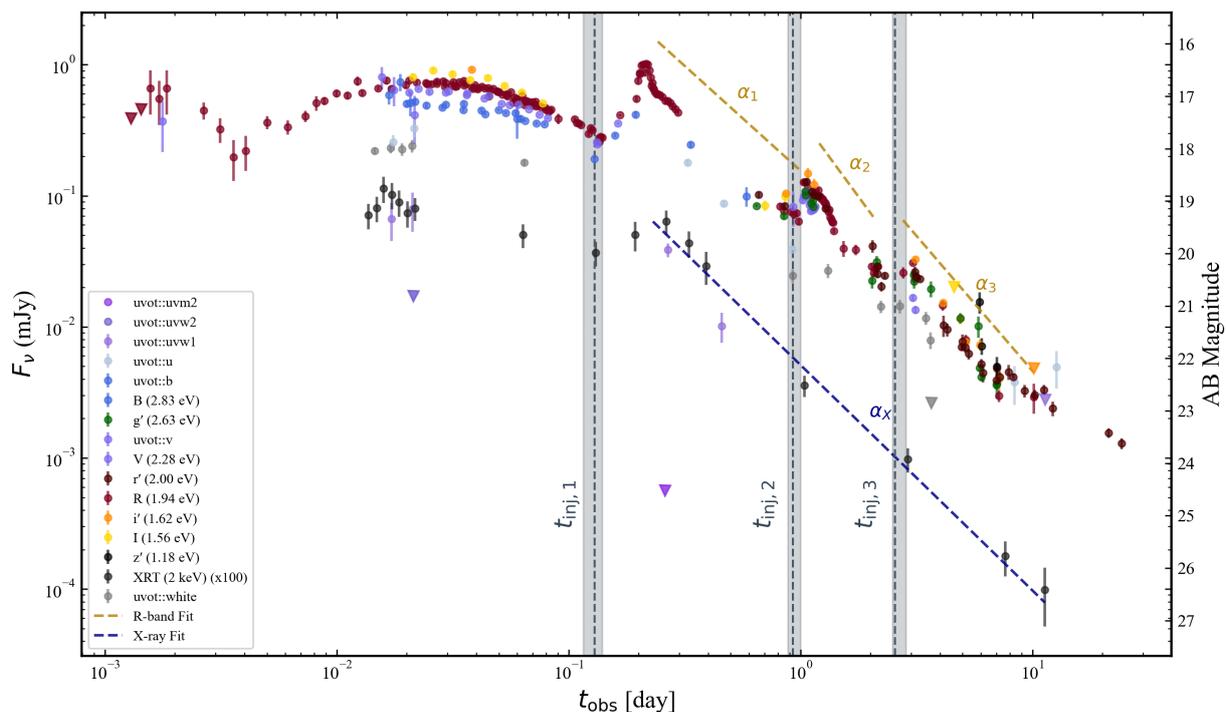


Fig. 5. Observations from this work. Apparent magnitudes corrected for the Milky Way extinction with the calibration of the Milky Way dust maps from (Schlafly & Finkbeiner 2011a). $t_{\text{inj},1}$, $t_{\text{inj},2}$, and $t_{\text{inj},3}$ correspond to the time of the first ($T - T_0 = 0.129^{+0.011}_{-0.013}$), second ($T - T_0 = 0.926^{+0.074}_{-0.042}$), and third ($T - T_0 = 2.55^{+0.301}_{-0.05}$) injections in days (see section 3). For clarity, XRT flux densities are scaled by x100 in this plot, and the AB-magnitude axis reflects the corresponding scaled flux densities. The dashed lines show the power-law fits to the afterglow. α_1 , α_2 , and α_3 correspond to the temporal decay indices in the R band, which are -1.6 , -2.41 , and -2.06 , respectively. α_X is the decay index in the XRT band, which has a value of -1.72 . [RG: connecting the X-ray emission with a single power law is problematic since it occurs during the rebrightening episodes and therefore likely doesn't maintain a single temporal index, just like the optical emission.] The R-band temporal decay fits are shown with a +0.4 dex vertical offset to aid visualization.

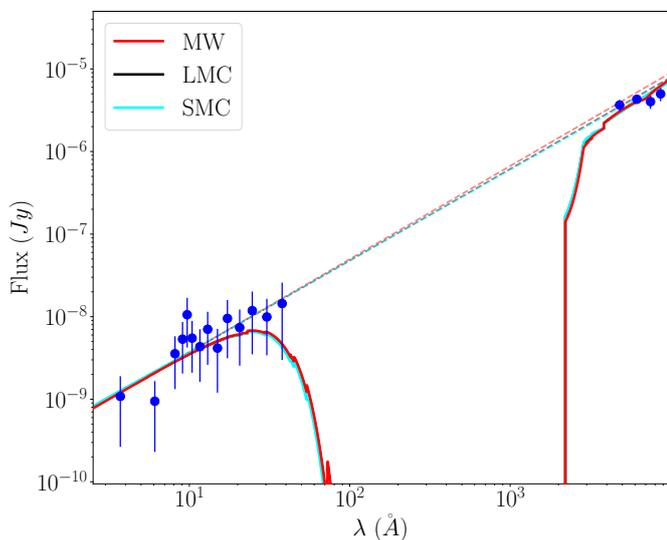


Fig. 6. X-ray-to-optical SED of GRB 250129A at $t - t_0 \sim 7.04$ days using the MW (red), LMC (black), and SMC (cyan) extinction curves. **Dashed lines:** intrinsic simple power law model of the afterglow. **Solid lines:** Best fits to the data, including the X-ray absorption and the optical extinction.

In light of these results, we used a no-host dust extinction scenario for the later analyses and didn't apply further correction.

3.2. Host Galaxy

We identified two bright possible host galaxies, SDSS 1237655125552333194 (G1) at $z = 0.42$ and SDSS 1237655125552333205 (G2) at $z = 0.26$, with spectroscopic redshifts provided by the Sloan Digital Sky Survey (SDSS) Data Release 12 (DR12) (Ahumada et al. 2020). We also included two faint galaxies identified in the Legacy Survey Catalog: G3 (ra:198.6775,dec:5.0292) and G4 (ra:198.6784, dec: 5.0317) with an estimation of a photometric redshift of $z_{\text{phot}} = 0.69$ for G3, and $z_{\text{phot}} = 0.64$ for G4, respectively. These four galaxies and their characteristics are presented in table 1 with redshift (z), magnitude in m_r , the projected angular separation R_0 between the GRB and the galaxy, the offset, and the probabilities of chance alignment $P_{\text{ch}}(< R_0)$.

We use Eq. 1–3 from Bloom et al. (2002) and the galaxy number counts from deep optical imaging (Metcalf et al. 2001; Kashikawa et al. 2004; McCracken et al. 2003), we estimate the probability of finding an unrelated galaxy of magnitude m_r or brighter within the vicinity of GRB 250129A (see Section 3.5 from Becerra et al. 2023):

The P_{ch} is $> 20\%$ for G2, G3 and G4, making them unlikely host galaxies. For G1, even though the P_{ch} value is $\sim 2\%$, its spectroscopic redshift does not match the redshift estimated for GRB 250129A. Therefore, despite the **low probability**, we also consider it unrelated to our event.

Table 1. Galaxies in the neighborhood of GRB 250129A. Is described for each galaxy: label (see text), redshift (z), magnitude in m_r , the projected angular separation R_0 between the GRB and the galaxy, the offset, and the probabilities of chance alignment $P_{\text{ch}}(< R_0)$. The asterisk in the photometric value indicates that it is a photometric redshift.

| | z | m_r | R_0 ["] | Offset [kpc] | $P_{\text{ch}}(< R_0)$ |
|----|-------|------------------|-----------|--------------|------------------------|
| G1 | 0.42 | 20.30 ± 0.05 | 4.48 | 49.99 | 2.08 |
| G2 | 0.26 | 21.00 ± 0.10 | 14.82 | 94.66 | 29.10 |
| G3 | 0.69* | 23.10 | 6.85 | 139.03 | 36.20 |
| G4 | 0.64* | 22.64 | 7.85 | 145.32 | 32.62 |

4. Interpretation

To model the afterglow emission before the rebrightening episodes seen in the optical and X-rays, we first consider the simple and standard afterglow model of a thin and ultrarelativistic spherical shell. This serves as a good approximation for a uniform top-hat jet viewed on-axis at times before the jet-break time. The shell propagates through the external medium that has number density $n_{\text{ext}}(R) = n_0(R/R_0)^{-k} = AR^{-k}$ with R the distance from the explosion center, k the index of the density profile and n_0 the density defined at a fixed R_0 . It is slowed down as it sweeps up this medium in its path. This gives rise to a two-shock structure, where a forward shock propagates ahead of the shell and shock heats the swept-up medium, while a reverse shock propagates through the shell, shock-heats it, and extracts its kinetic energy. The shell starts to decelerate when the swept-up mass $M_{\text{sw}}(R) = 4\pi m_p n_{\text{ext}}(R)R^3/(3-k) = M_0/\Gamma_0$, where $M_0 = E_{\text{k,iso}}/\Gamma_0 c^2$ and $\Gamma_0 \gg 1$ are the baryon load and coasting bulk Lorentz factor (LF) of the shell, respectively, $E_{\text{k,iso}}$ is its isotropic-equivalent kinetic energy after the prompt phase, and m_p and c are the proton mass and speed of light. The corresponding deceleration radius is given by $R_{\text{dec}} = [(3-k)E_{\text{k,iso}}/4\pi m_p c^2 A \Gamma_0^2]^{1/(3-k)}$, where the bulk of the kinetic energy of the shell is given to the shocked swept-up medium that causes the forward shock afterglow emission to peak. At $R > R_{\text{dec}}$, the dynamical evolution of the shell follows the Blandford & McKee (1976) solution where its bulk LF declines as a power law in radius with $\Gamma(R) \propto R^{-(3-k)/2}$, as dictated by energy conservation.

We model the emission coming from the forward shock using the standard afterglow theory (Sari et al. 1998b). The shock accelerates a large fraction of the electrons in the swept up medium into having a power-law energy distribution, with comoving number density $n_e(\gamma) \propto \gamma^{-p}$ for $\gamma > \gamma_m$ and where γ is the LF of the electrons and γ_m is the LF of the minimal energy electrons. These electrons hold a fraction ϵ_e of the total internal energy in the shocked medium, while a fraction ϵ_B goes into generating and/or amplifying small-scale magnetic fields. The accelerated electrons then cool behind the shock front by emitting synchrotron radiation. The power-law temporal index (α) and the spectral index (β) of the afterglow emission ($F_\nu \propto t^\alpha \nu^\beta$) are related through the *closure relations*, where slow-cooling emission produced at a frequency $\nu_m < \nu < \nu_c$ (with ν_m the peak synchrotron frequency of minimal-energy electrons and ν_c the cooling-break frequency (Granot & Sari 2002)) has $\alpha = -3(p-1)/4$ and $\beta = -(p-1)/2$ when $k = 0$. We exploit these relations below to check for consistency and infer the value of p .

4.1. Empirical fitting and probing external shock scenario

To be modified We investigated different temporal and spectral slope on different episodes of the light curves. The early (< 104 s) optical and X-ray data can be modelled with simple power-laws having slopes $\alpha = 0.93 \pm 0.01$ and $\alpha = 0.97 \pm 0.04$, respectively (see Figure 1). We interpret this emission to come from the external forward shock and the similarity in the temporal decay suggests that both emissions are produced by the same

Synchrotron power-law segment (which is at $t < t_{\text{dec}}$). Comparing the early optical decay slope $\alpha = 0.93 \pm 0.01$ with the expected one in a constant ambient density ($\alpha = 3(1-p)/4$), we obtain an electron power-law index ($p = 2.24 \pm 0.01$) that is consistent with values reported for other GRBs (e.g., Kumar & Zhang 2015). This result is incompatible with a wind environment, where the expected decay slope ($\alpha = (13-p)/4$) would imply $p = 1.57 \pm 0.01$, an unusually low value for GRBs (see, e.g., Zhang & Mészáros 2004; Chevalier & Li 2000).

As the $\alpha_{R,1,2,3}$ numbers in the three segments of the temporal analysis in the R band are given respectively, we can obtain the numbers of p as 3.13, 4.21, and 3.75 respectively by the relation of $\alpha = 3(p-1)/4$ in the homogeneous environment. We also estimate the numbers of p as 2.47, 3.55, and 3.08, respectively, by the relation of $\alpha = (3p-1)/4$ in the wind environment. It seems that the results are not consistent to the predictions of the external shock in the standard fireball model.

4.2. Agnostic approach

Framework and analysis period We aim to extract the physical estimates of the jet and emission properties by analyzing the light curve data with the AFTERGLOWPY model (Ryan et al. 2020) using the Bayesian inference framework NMMA (Pang et al. 2023). The AFTERGLOWPY package models the GRB afterglow as the result of synchrotron emission from accelerated electrons. Here we make the explicit assumption that the jet propagates inside a constant density interstellar medium (ISM) with $n_{\text{ext}} = n_{\text{ISM}}$. The jet structure is assumed as a top-hat jet for which the isotropic-equivalent kinetic energy, $E_{\text{k,iso}}$, is constant across the jet aperture with half-opening angle θ_j . Moreover, the dynamical evolution of the jet in AFTERGLOWPY does not consider a coasting phase and instead makes the simplifying assumption that it has already decelerated and follows the asymptotic power-law decline of its bulk Lorentz factor with radius. For this reason, when analyzing the data from GRB 250129A with AFTERGLOWPY, we exclude early data within the first 0.05 days (4320 s) post-burst, as these data points show a rising light curve that is likely due to a jet coasting phase and can not be properly modeled in AFTERGLOWPY.

Energy injections in a phenomenological approach In order to capture the rebrightening epochs from GRB 250129A's afterglow, we established an ad-hoc prescription that allows the jet energy to vary with time. Specifically, we introduce an energy injection parameter $\Delta \log_{10} E$ that, starting from time t_{inj} , linearly increases the jet energy within the time interval (see Appendix E for further details and explanation regarding the energy injection computation within NMMA). Naturally, this parametrization can be extended to include multiple energy injections. We emphasize that this prescription represents a phenomenological approach and does not account for the mechanism underlying the increase in jet energy nor its exact temporal dependence. Despite the limitations in our modeling prescriptions, the ad hoc increase of the jet energy still allows us to phenomenologically recover the rebrightening in the afterglow light curve and statistically investigate the number of rebrightenings and their approximate duration. Details of this ad-hoc energy injection prescription are laid out in App. E.

To infer the posterior $p(\vec{\theta}|d)$ from the light curve data d , we sample the parameter space of the model using the nested sampling algorithm as implemented in PYMULTINEST (Feroz et al. 2009; Buchner et al. 2014). In particular, we use the likelihood function $\ln \mathcal{L}(\vec{\theta}|d)$, which compares the observed magnitudes to the model predictions from AFTERGLOWPY. The model parameters and priors are listed in Table 2. In addition to the model parameters, NMMA also samples a nuisance parameter σ_{sys} that accounts for systematic uncertainty in the modeling. Throughout the analysis, we fix the redshift at $z = 2.151$ (Sec. 1), corresponding to a luminosity distance of $d_L = 17.3$ Gpc. We begin by establishing a reference baseline to evaluate the statistical significance of the observed rebrightening epochs. Specifically, we select data from the time interval between 0.05 and 0.2 days, which we refer to as the “early time” dataset. The posterior light curves estimated using the data from this interval serve as a proxy for a standard GRB afterglow in our subsequent analysis (see Table 2). Using posterior light curves derived from the “early time” data, we compute the average chi-squared statistic, $\langle \chi_j^2 \rangle$, for each data point (see Appendix E for details). In the R band, the computed $\langle \chi_j^2 \rangle$ values reveal three distinct rebrightening phases spanning the intervals [0.15, 1] days, [1, 3] days, and [3, 30] days (see Figure 5). To investigate these features, we apply the ad hoc energy injection model described in Eq. (E.1) (see Appendix E for details) and analyze the full dataset beyond 0.05 days. Parameter priors are listed in Tab. 2.

In total, four models are considered, namely, one without energy injection, ones with 1, 2 and 3 energy injection epochs. The posterior distributions for the four models considered are summarized in Tab. 3 and visualized in Fig. 7. As described in Ref. Pang et al. (2023), the parameter σ_{sys} is included to account for the systematic uncertainty within the lightcurves modeling. Comparing the inferred systematic uncertainty across models with varying numbers of energy injection epochs to the baseline model without injections, we observe a general decreasing trend. This suggests that including energy injections improves the model’s ability to fit the data.

We also compare the maximum likelihood values and compute the Bayes factors between the models, as reported in Tab. 3. Our analysis shows that models with one, two, or three injection epochs yield higher maximum likelihoods and are favored by the Bayes factor. However, in the case of three injections, the (ln-) Bayes factor ($\ln \mathcal{B} \sim 6$) relative to the two-injection model is modest. Furthermore, the estimated fractional energy injected associated with the third injection is notably small. This is consistent with the best-fit light curves, as there is minimal difference between the 2-injection and 3-injection light curves shown in Fig. 8, leading us to conclude that only the first two rebrightenings are statistically significant.

Despite the apparent consistency between the model and data for each individual rebrightening phase when energy injection is included, the inferred physical parameters, e.g., the On-axis isotropic equivalent energy $E_{k,\text{iso}}$ and the electron distribution power-law index p , vary significantly across the different epochs. Energy injection provides a physically motivated explanation for afterglow rebrightenings. One possible interpretation is the refreshed-shock scenario, in which the ejecta possess a distribution of Lorentz factors rather than a single characteristic value. As the forward shock decelerates, slower but energetically significant ejecta catch up with the blast wave and re-energize it, leading to a rebrightening of the afterglow light curve (Sari & Mészáros 2000b). This framework is also adopted by Laskar et al. (2015b), who model energy injection as arising from a continuous dis-

tribution of Lorentz factors released over a time interval short compared to the afterglow timescale. The variation between the inferred parameters for GRB 250129A indicates that such energy injection alone is insufficient to capture the underlying physics in a self-consistent manner.

[RG: I see two problems with energy injection by having ejected shells with radially stratified velocity. (i) Typically this type of energy injection is expected to give rise to a single rebrightening episode and not multiple such episodes, and (ii) the lightcurve temporal slope after injection must remain the same as the pre-injection lightcurve if the emission continues to arise from the same synchrotron power-law segment, i.e. no crossing of break frequencies. Here we notice that the slope becomes steeper and changes after each injection, which lends only weak support to this scenario.]

4.3. Refreshed Shocks scenario: Shell Collisions

The multiple pulses in the prompt emission phase suggest that there are multiple mass shells launched by the central engine. We consider that the earliest launched shell (outermost in the radial direction, or the external shock) has a bulk Lorentz factor (LF) of $\Gamma_{0,1} \gg 1$, which starts to decelerate at $R \geq R_{\text{dec}}$. Later shells ejected with bulk LFs $\Gamma_{0,i} \gg 1$, with $i = (2, 3, 4)$, propagate almost unimpeded and may collide with the outer shell in succession, thereby dissipating their kinetic energy and causing potential rebrightening episodes (e.g. Kumar & Piran 2000b; Sari & Mészáros 2000c; Zhang & Mészáros 2002). The correspondence between the prompt pulses and shells, and the timing analyses on the temporal features, are crucial to identify whether collisions could occur, which has been applied in the explanation of GRB 140304A (Laskar et al. 2018), GRB 240529A (Sun et al. 2024), GRB 060729 (Geng et al. 2025b), and GRB 250221A (Angulo-Valdez et al. 2025) recently. When the two shells collide, another set of forward and reverse shocks develops, where the FS shock heats the already relativistically hot material of the outer shell, while the RS shock heats the inner shell.

The first optical rebrightening episode starts at $T_1 \simeq 1.1 \times 10^4$ s. Since the rebrightening occurs after the peak of the light curve, it is clear that the outermost shell has already decelerated. In general, for an ultrarelativistic shell with dynamics $\Gamma^2 \propto R^{-m}$, where $m = 0$ for a coasting shell at $R < R_{\text{dec}}$ and $m = 3 - k$ for a decelerating shell with self-similar evolution at $R > R_{\text{dec}}$, the on-axis arrival time of radiation is $T_z \equiv T/(1+z) \simeq R/2(1+m)\Gamma^2 c$. Then, given $\hat{T}_1 \equiv T_1/T_{\text{dec}}$ ($T_{\text{dec}} \simeq T_{\text{pk}} \simeq 2 \times 10^3$ s), we can calculate the radius at which shocks develop in the two colliding shells, such that (e.g., Laskar et al. 2018; Angulo-Valdez et al. 2025)

$$\hat{R}_1 \equiv \frac{R_1}{R_{\text{dec}}} = [(4-k)\hat{T}_1]^{1/(4-k)} \simeq 2.2 \quad (k=0), \quad (1)$$

with the assumption that the material that makes the dominant contribution to the re-brightened emission is moving with LF $\sim \Gamma_1$. To reach radius R_1 , the outer shell takes lab-frame time of $t_1 = t_{\text{em},1} + R_1/c + (\hat{R}_1^{4-k} - 1)T_{\text{dec},z}/(4-k)$. To reach the same radius, the inner shell takes lab-frame time $t_1 = t_{\text{em},2} + R_1/\beta_{0,2}c \simeq t_{\text{em},1} + \delta t_{\text{em},12} + (1+1/2\Gamma_{0,2}^2)R_1/c$, where $t_{\text{em},1} < t_{\text{em},2} < T_{90}/(1+z) \simeq 83$ s and $\delta t_{\text{em},12}$ is the waiting time between the ejection of the first two mass shells. Since $\delta t_{\text{em},12}(1+z)/T_{\text{dec}} \ll 1$, it can be neglected when equating the lab-frame arrival times of the two shells at R_1 , which yields an estimate of the contrast between the

Table 2. Parameters employed and the associated prior bound in our Bayesian inferences. Three sets of priors are used for each of the anomaly peaks.

| Parameter | Prior bound |
|---|--|
| (log ₁₀ -) On-axis isotropic equivalent energy $E_{k,\text{iso}}$ [erg] | [47, 57] |
| (log ₁₀ -) Ambient medium's density n_{ISM} [cm ⁻³] | [-6, 2] |
| (log ₁₀ -) Energy fraction in electrons ϵ_e | [-4, 0] |
| (log ₁₀ -) Energy fraction in magnetic field ϵ_B | [-8, 0] |
| Electron distribution power-law index p | [2.01, 3] |
| Viewing angle [degree] | [0, 36] |
| Jet core opening angle θ_j [degree] | [0.6, 20] |
| Systematic error σ_{sys} [mag] | [0, 2] |
| Start time of energy injection t_{inj} [day] | [0.07, 0.3], [0.7, 1.3], [2.5, 3.5] |
| Duration of energy injection Δt_{inj} [day] | [0.001, 0.3], [0.001, 0.4], [0.001, 1] |
| (log ₁₀ -) Fractional energy injected $\Delta \log E_{k,\text{iso}}$ | [0, 3], [0, 4], [0, 4] |

Table 3. Parameters employed in our Bayesian inferences. We report maximum likelihood values at 95% credibility for various sub-datasets considered.

| Parameter | No injection | 1-injection | 2-injection | 3-injection |
|---|---|---|---|---|
| (log ₁₀ -) On-axis isotropic equivalent energy $E_{k,\text{iso}}$ [erg] | 52.53 ^{+0.43} _{-0.02} | 53.72 ^{+0.95} _{-0.58} | 53.85 ^{+0.80} _{-0.18} | 54.12 ^{+0.93} _{-0.36} |
| (log ₁₀ -) Ambient medium's density n_{ISM} [cm ⁻³] | -0.31 ^{+2.3} _{-0.22} | -0.32 ^{+2.32} _{-3.45} | 0.82 ^{+0.81} _{-3.8} | -0.84 ^{+1.53} _{-4.65} |
| (log ₁₀ -) Energy fraction in electrons ϵ_e | -0.01 ^{+0.0} _{-0.44} | -0.93 ^{+0.45} _{-0.84} | -0.61 ^{+0.14} _{-0.81} | -0.89 ^{+0.29} _{-0.96} |
| (log ₁₀ -) Energy fraction in magnetic field ϵ_B | -1.86 ^{+1.66} _{-0.35} | -3.71 ^{+2.21} _{-1.23} | -5.26 ^{+2.31} _{-0.48} | -4.25 ^{+2.78} _{-0.9} |
| Electron distribution power-law index p | 2.29 ^{+0.09} _{-0.06} | 2.68 ^{+0.09} _{-0.12} | 3.00 ^{+0.0} _{-0.03} | 3.00 ^{+0.00} _{-0.06} |
| Viewing angle [degree] | 7.15 ^{+8.85} _{-0.5} | 13.44 ^{+3.99} _{-9.94} | 0.13 ^{+9.61} _{-0.13} | 14.79 ^{+4.38} _{-10.59} |
| Jet core opening angle θ_j [degree] | 9.75 ^{+10.25} _{-0.2} | 16.62 ^{+3.38} _{-10.76} | 16.66 ^{+3.34} _{-5.88} | 15.93 ^{+4.07} _{-10.92} |
| Time of 1 st energy injection $t_{\text{inj},1}$ [day] | - | 0.128 ^{+0.021} _{-0.015} | 0.126 ^{+0.012} _{-0.015} | 0.129 ^{+0.011} _{-0.013} |
| Duration of 1 st energy injection $\Delta t_{\text{inj},1}$ [day] | - | 0.070 ^{+0.024} _{-0.033} | 0.075 ^{+0.019} _{-0.021} | 0.075 ^{+0.014} _{-0.018} |
| (log ₁₀ -) 1 st Fractional energy injected $\Delta \log E_1$ | - | 0.51 ^{+0.057} _{-0.065} | 0.512 ^{+0.059} _{-0.039} | 0.515 ^{+0.059} _{-0.033} |
| Time of 2 nd energy injection $t_{\text{inj},2}$ [day] | - | - | 0.974 ^{+0.031} _{-0.077} | 0.926 ^{+0.074} _{-0.042} |
| Duration of 2 nd energy injection $\Delta t_{\text{inj},2}$ [day] | - | - | 0.007 ^{+0.102} _{-0.006} | 0.083 ^{+0.037} _{-0.082} |
| (log ₁₀ -) 2 nd Fractional energy injected $\Delta \log E_2$ | - | - | 0.166 ^{+0.008} _{-0.043} | 0.204 ^{+0.013} _{-0.034} |
| Time of 3 rd energy injection $t_{\text{inj},3}$ [day] | - | - | - | 2.55 ^{+0.301} _{-0.05} |
| Duration of 3 rd energy injection $\Delta t_{\text{inj},3}$ [day] | - | - | - | 0.282 ^{+0.294} _{-0.281} |
| (log ₁₀ -) 3 rd Fractional energy injected $\Delta \log E_3$ | - | - | - | 0.053 ^{+0.02} _{-0.044} |
| Systematic error σ_{sys} [mag] | 0.38 ^{+0.03} _{-0.04} | 0.24 ^{+0.03} _{-0.02} | 0.19 ^{+0.03} _{-0.01} | 0.17 ^{+0.03} _{-0.01} |
| (ln-) likelihood ratio $\ln \Lambda$ | reference | 87.17 | 128.52 | 144.15 |
| (ln-) Bayes factor $\ln \mathcal{B}$ | reference | 78.88 ± 0.22 | 110.44 ± 0.24 | 116.95 ± 0.25 |

initial LFs of the two shells,

$$\frac{\Gamma_{0,1}}{\Gamma_{0,2}} \approx \sqrt{\frac{\hat{R}_1^{4-k} - 1}{(4-k)\hat{R}_1}} \approx \frac{[(4-k)\hat{T}_1]^{(3-k)/2}}{\sqrt{4-k}} \approx 1.6 \quad (k=0), \quad (2)$$

where the second approximation assumes that $\hat{R}_1 \gg 1$. During the collision, the bulk Lorentz factor of the FS can be approximated as the velocity of the merged two shells, i.e.,

$$\Gamma_F \approx \left(\frac{\Gamma_1 m_1 + \Gamma_{0,2} m_2}{m_1/\Gamma_1 + m_2/\Gamma_{0,2}} \right)^{1/2} \in [\Gamma_1, \Gamma_{0,2}], \quad (3)$$

according to the conservation of energy and momentum, where m_1 and m_2 are the masses of the two shells, respectively. The co-moving thickness of the leading shell can be approximated as $\Delta_1 \approx \eta R_1/\Gamma_1 \approx 2\eta\Gamma_{0,2}^2 cT_{1,z}/\Gamma_1$ at T_1 , where η is a geometry factor that could be taken as $\eta = 1/4(3-k)$ from the consideration of particle number conservation for a homogeneous shell. Let β_{F1} denote the relative velocity between the forward shock and the leading shell. We may expect that the optical flare would reach

its peak luminosity when the FS has crossed the entire leading shell after an observational duration of (Geng et al. 2025b)

$$\begin{aligned} T_{\text{flare},1} - T_1 &\approx (1+z)\Gamma_F(1-\beta_F \cos(\min[\theta_j, 1/\Gamma_F])) \frac{\Delta_1}{\beta_{F1}c} \quad (4) \\ &\approx 2\eta\Gamma_{0,2}^2/(\Gamma_F\Gamma_1\beta_{F1})T_1 \\ &\in \left[\frac{\Gamma_{0,2}}{\Gamma_{0,1}} \hat{R}_1^{(3-k)/2}, \frac{\Gamma_{0,2}^2}{\Gamma_{0,1}^2} \hat{R}_1^{3-k} \right] \frac{2\eta}{\beta_{F1}} T_1 \end{aligned}$$

for $\theta_j > 1/\Gamma_F$, where the last range is obtained by taking the two extremes for Γ_F in Equation (3). As observation of the R band data gives a dimensionless timescale of $\delta\hat{t} = (T_{\text{flare},1} - T_1)/T_1 \approx 0.5$ for the rising phase of the first optical flare, Equations (1 - 4) suggest that $\eta \leq 0.12$ since $\beta_{F1} < 1$.

The analyses on the shock dynamics above show the conditions for the shell collision. We further conduct more accurate numerical calculations to verify that this scenario can well explain the multiple peaks in GRB 250129A with a set of reasonable parameters. Before collision, the dynamic of the external shock of the first outflow is described by a generic model based on energy

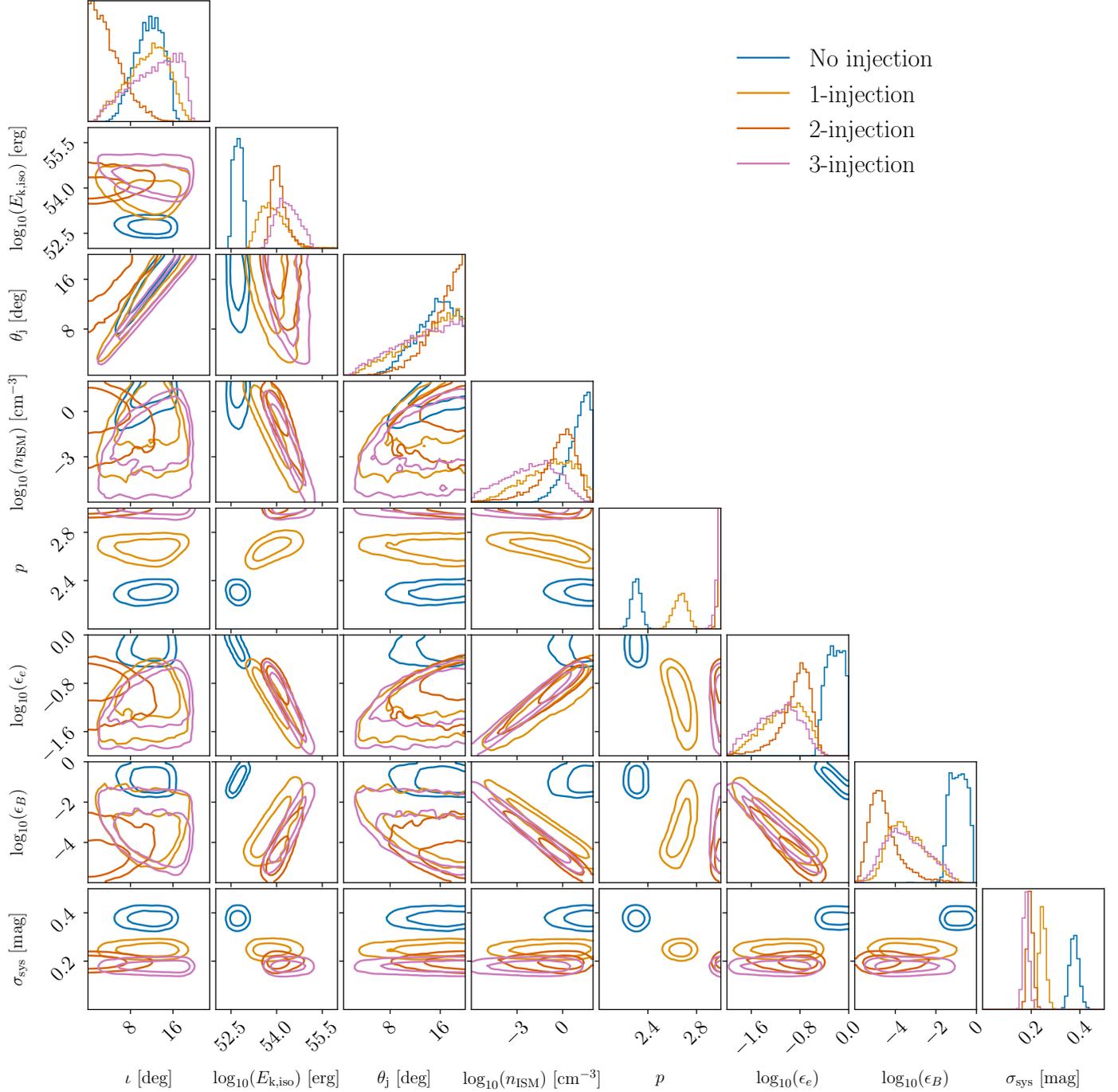


Fig. 7. Posterior of the GRB afterglow for each of the models (see section 4.2) considered using NMMA. Priors are given in Table 2. The different times on rebrighting (e.g., energy injections) are consistent with the light curve (see Figure 5).

conservation (Huang et al. 1999; Pe’er 2012). During collision, the dynamics of the FS/RS system is described by the mechanical model that incorporates the conservation of energy and momentum (Beloborodov & Uhm 2006; Geng et al. 2025a). We calculate the time-dependent electron spectrum heated by each shock by solving the continuity equation in energy space (Geng et al. 2018), and derive the resulting synchrotron and synchrotron self-Compton emission using standard formulae (Rybicki & Lightman 1979). In our calculations, the environment is assumed to be ISM-type for simplicity, and the accelerated post-shock electron spectrum is generalized as a Maxwellian component and a power-law component for each shocked/emitting region. This

hybrid spectrum is characterized by an energy fraction parameter defined as the nonthermal energy fraction of the total, and we set it to a typical value of ~ 0.4 following earlier studies for simplification (Giannios & Spitkovsky 2009; Gao et al. 2024). We fit the early afterglow within 10^4 s, produced by the outermost shell, using the standard Bayesian approach to derive its parameters: $E_{k,iso}$, $\Gamma_{0,1}$, θ_j , n_{ISM} , ϵ_e , ϵ_B , and p . We assume that subsequently launched shells share the same jet opening angle θ_j and circumburst density n_{ISM} as the outermost shell. To account for the observed optical flares, we introduce two additional shells that are launched after the outermost shell. Since their initial bulk Lorentz factors are only of order several tens, deceleration is not

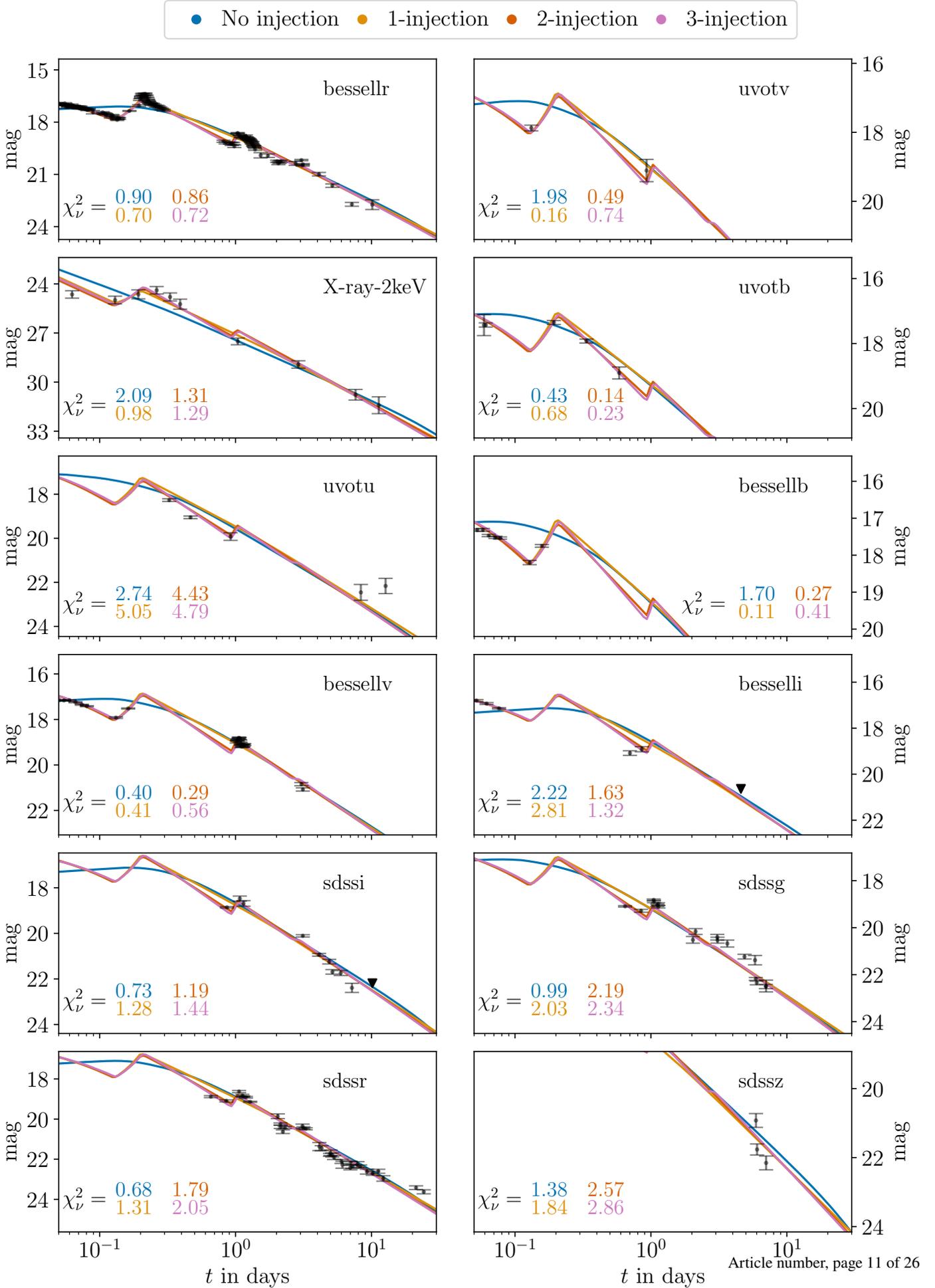


Fig. 8. Best-fit light curves of the GRB afterglow, together with the reduced χ^2 of each filter, for each of the models considered.

Table 4. Parameters employed in the afterglow fitting within the framework of multiple shell collisions.

| Parameters | First Shell | Second Shell | Third Shell | First Collision | | | Second Collision | | |
|--------------------------------|-------------------------|--------------|-------------|------------------------|------|------|------------------|------|------|
| | | | | FS | RS* | ES | FS | RS* | ES |
| $E_{k,iso}$ (10^{53} erg) | $1.70^{+0.12}_{-0.11}$ | 10.0 | 8.0 | | | | | | |
| Γ_0 | $97.72^{+2.28}_{-4.40}$ | 39.0 | 24.5 | | | | | | |
| θ_j (rad) | | | | $0.10^{+0.02}_{-0.02}$ | | | | | |
| n_{ISM} (cm^{-3}) | | | | $1.05^{+0.27}_{-0.16}$ | | | | | |
| ϵ_e | $0.09^{+0.01}_{-0.00}$ | | | 0.18 | 0.10 | 0.11 | 0.10 | 0.10 | 0.12 |
| ϵ_B (10^{-3}) | $2.51^{+0.31}_{-0.32}$ | | | 10.0 | 10.0 | 2.0 | 10.0 | 10.0 | 2.0 |
| p | $2.07^{+0.00}_{-0.00}$ | | | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.4 |
| η | 0.12 | 0.12 | | | | | | | |

*Note that the microphysical parameters of RSs during two collisions are not constrained since their flux contribution could be ignored with typical values.

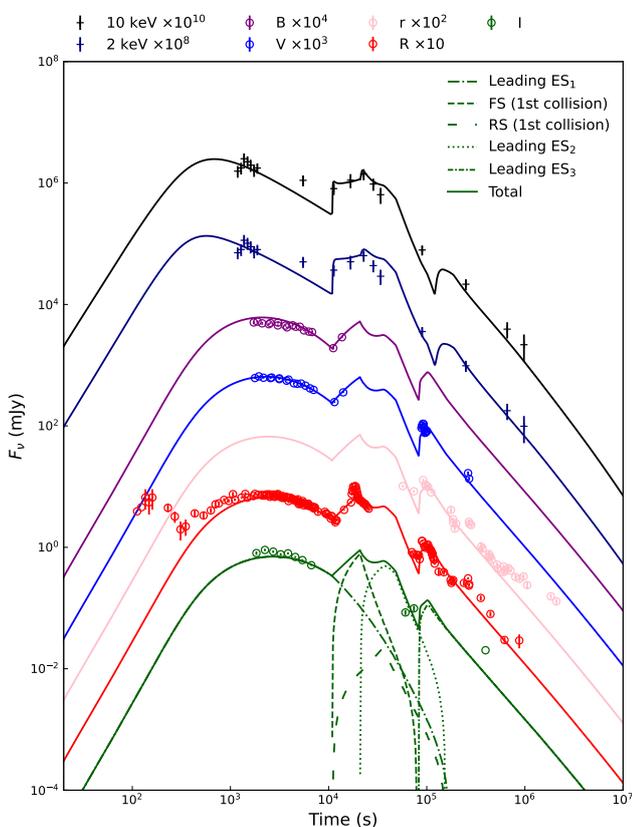


Fig. 9. Fit to the GRB afterglow within the scenario of shock collision. The dash-dotted line is the emission of the outermost external shock (marked as ES_1) propagating in the environment for the first outflow. The dashed and loosely dashed line represents emission from the forward shock (FS) and the reverse shock (RS) during the collision, respectively. The dotted line is the emission of the external shock at the second stage (marked as ES_2) after the FS crossing the leading shell, which is refreshed again to and marked as ES_3 at the third stage (densely dashed-dotted lines) by the second collision near 1 day. Since the crossing timescales of the FS/RS during the second collision are relatively shorter and their flux contribution are sub-dominant, they are not shown by individual lines for clarity. The total flux from all emission components is given by the solid line for each band.

yet significant; these shells therefore move at nearly constant speed until they catch up and collide with the preceding outermost shell, producing the optical flares. During each collision, the equation of state of the material ahead of the FS is determined by calculating the averaged Lorentz factor of material accumulated by the leading shock with adiabatic cooling accounted (e.g., Nava et al. 2013). The parameters of the subsequent two shells and the relevant collisions are chosen after several trials around typical values. As shown in Fig. 9, the multi-wavelength afterglow and two significant rebrightenings could be well fitted with a set of parameters listed in Tab. 4. For the first collision that generates the intense optical flare, the adopted $\Gamma_{0,1} \approx 100$ and $\Gamma_{0,2} \approx 40$ generally align with Equation 2. The optical flare is mainly contributed by the FS as the FS sweeps and re-accelerates the material collected from the environment by the leading shell. After each collision, the FS crosses the entire leading shell, and the merged shell evolves into a new leading/outmost external shock propagating in the environment. The shell collision scenario provides details of the shock interaction in comparison with the traditional energy injection scenario, while the fitting results of both scenarios are consistent with each other.

5. Conclusion and discussion

GRB 250129A is a very intriguing long GRB with an extended prompt emission ($T_{90} > 250$ s) that was observed in both optical and gamma-rays. The afterglow presents multiple rebrightening episodes across the UV, optical, and X-ray bands. In this paper, we present a comprehensive multi-wavelength dataset. Through an extensive and rapid follow-up campaign involving about 20 instruments, both space- and ground-based facilities, including GRANDMA and its partners, such as Colibri, KAIT, Skynet, we obtained a well-sampled, time-resolved coverage of the afterglow, capturing its complex temporal evolution over ~ 24 days (see sec 2). By employing temporal and spectral modeling, we first demonstrate [RG: Perhaps you meant something else, but I'm not sure why it needed any demonstration. It is obvious just by simply looking at the lightcurve, no?], with statistical significance, the presence of two distinct rebrightening episodes, the third being well less significant (see sec 4.2). We also introduce a new phenomenological approach aimed at probing the temporal evolution of the jet energy. Although this approach does not

explicitly account for the underlying physical mechanisms, it provides clear evidence for an evolution of the jet energy over time that explains the re-brightenings (see sec 4.2). We could exclude the hypothesis of single external-shock evolution or a one-time energy injection. [RG: The last two sentences are rather obvious and do not really provide “clear” evidence of anything. The only way to explain the rebrightenings is to add energy to the blast wave. The phenomenological approach does not add more to our understanding and only offers one possible explanation for the lightcurve.]

We explored the origin of multiple rebrightening episodes using a sequence of refreshed shocks produced by collisions between shells with different bulk Lorentz factors ejected during the prompt emission phase (see sec 4.3). We adopted a kinetic approach (the code to be publicly published by Geng et al. in preparation) to calculate the dynamics and radiation from such collisions. Although the current analysis requires the introduction of additional microphysical parameters to describe the separate emission components and does not involve a complete Bayesian inference, the observed flares could be broadly interpreted using a reasonable set of typical parameters ($\epsilon_e \simeq 0.1$, $\epsilon_B \simeq 10^{-3}-10^{-2}$). This outcome supports the physical feasibility of the scenario. Future work incorporating robust priors on microphysical parameters from simulations and additional multi-wavelength observations (e.g., in the GeV and radio bands, if available) would enable more rigorous parameter constraints.

Finally, we may ask whether the scenario explored in this work should be considered the preferred one compared to alternative scenarios that were not investigated [RG: Such as ?]. First, the prompt emission displayed four distinct emission episodes in gamma-rays and at least one in optical, likely corresponding to multiple relativistic shells interacting during the afterglow phase. The optical rebrightenings in GRB 250129A exhibit a steep temporal index, in contrast to the shallower behaviors seen in some GRBs (Filgas et al. 2011; Nardini et al. 2014) at a comparable time ($\sim 10^4$ s) in the afterglow phase. Such steepness supports the interpretation that these are new emission components produced by shell collisions, rather than results of a gradual energy injection process, e.g., by the multiple shells having a radial velocity structure or where the central engine episodically injects energy into the blast wave. The latter scenario is challenging to justify as it is not clear how any central engine, a magnetar or black hole, might influence the blast wave energetics at such great distances away from it. The observed trend of decreasing relative amplitudes in the optical rebrightenings suggests a decline in the velocities of the trailing shells. This interpretation becomes problematic since the *compactness* argument demands the different shells to be moving with ultra-relativistic ($\Gamma_0 \gtrsim 100$) velocities in order to emit the gamma-rays. If multiple jets arise from accretion onto the central compact object (e.g., a black hole), the properties of these shells could provide valuable insights into the system’s accretion history and jet-launching mechanisms. However, the kinetic energy of the rear shells may not be well constrained due to the lack of simultaneous, high-quality X-ray data and the degeneracy of microphysical parameters during the collision.

Besides, one other possible explanation for the rebrightenings not investigated further in this work arises from the moment when a relativistic blast wave encounters a varying external density profile near the GRB progenitor, which is expected due to strong winds and violent mass eruptions (Ramirez-Ruiz et al. 2001). However, previous work suggests that the density jump may not be sufficient to account for the intense optical flare at 10^4 s observed in GRB 250129A (Nakar & Granot 2007; van Eerten et al. 2009; Gat et al. 2013; Geng et al. 2014). As obser-

vational coverage continues to improve in a very timely manner, the detection of more GRBs exhibiting similar behavior could provide deeper insight into the prolonged activity and complex dynamics of GRB central engines.

Data Availability

The raw measurements are all public and can be retrieved at the GRB 250129A SkyPortal Public Page. The images can be shared on a reasonable request.

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Appendix A: Contribution

D. Akl and S. Antier are the main contributors to the work, including the analysis and writing across all sections, coordination, and organization of contributors related to observational and high-energy results. M. Pillas is the coordinator of the article. Z. Wang and S. Antier are the main authors of Sec. 2.1. They received help from A. Lien.

D. Akl and M. Molham are the main contributors and authors of Sec. 2.2. D. Akl and M. Molham are the authors of Sec. 2.3 related to Space observations with the help of S. Oates and A. de Ugarte Postigo, and D. Akl is the main author related to Ground observations, with the coordination and contribution of S. Antier and S. Karpov.

N. Rakotondrainibe is the main contributor of Sec. 3.1. R. L. Becerra is the main contributor of Sec. 3.2.

J. Mao and R. Strausbaugh are the main authors of Sec. 4.1. P. Pang and H. Koehn are members of the paper writing team and wrote Sec. 4.2. J.J Geng is the main contributor of Sec. 4.3. R. Gill and T. Laskar contributed to reviewing Sec. 4 as well as guiding the modeling of the rebrightening episodes.

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N. Globus and N. Guessoum contributed to the review and edition of the full article to improve the quality of the article.

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Appendix C: X-ray Data Reduction: Additional Details

We rebinned the XRT light curve into non-continuous segments. Each of these segments was treated as a distinct temporal window, within which we calculated the mean flux and its standard deviation. This approach allows us to combine temporally proximate measurements, hence increasing the signal-to-noise ratio of temporally close data points and retaining the overall time evolution of the light curve. For each bin, we calculated the average time in the bin, average flux density, and the error on the flux density, which was calculated as the larger of the standard deviation of the flux values or the average propagated error.

To convert the flux density from 10 keV to 2 keV, and derive the AB magnitudes, we used the standard energy scaling relation for flux densities in frequency space:

$$F_\nu(E_2) = F_\nu(E_1) \left(\frac{E_2}{E_1} \right)^{\Gamma-1},$$

where $E_1 = 10$ keV, $E_2 = 2$ keV, and $\Gamma - 1 = 0.94$ for the photon index $\Gamma = 1.94$, obtained from the online Swift Time-Averaged Spectrum footnote https://www.swift.ac.uk/xrt_spectra/01285812/.

This conversion is motivated by the fact that *Swift*-XRT's effective area, and hence its sensitivity, declines significantly at higher energies, making 10 keV flux measurements noisier and less reliable. We selected 2 keV as a reference energy for spectral scaling and magnitude conversion, as it lies near the logarithmic midpoint of the *Swift*-XRT energy band (0.3–10 keV).

The output flux values were subsequently converted to AB magnitudes using the standard relation:

$$m_{AB} = -2.5 \log_{10} \left(\frac{F_\nu}{3631 \text{ Jy}} \right)$$

where F_ν is the flux at 2keV in Jy and 3631 μ Jy corresponds to the flux density of an object with an AB magnitude of 0.

The data reduction and spectral analysis were conducted using HEASoft v6.34 using the *XRT tool xrtpipeline* (v0.13.7) on the three XRT spectra on 2025-01-29, with the latest updated calibration data files (CALDB, released on 2024 February 28). Spectral modeling and parameter estimation were performed using XSPEC v12.14.1, employing *c*-statistics as the fitting method (Fit.statMethod = "cstat"), which is particularly suited for low-count Poisson-distributed X-ray data as it provides a more reliable parameter estimation compared to the traditional χ^2 fitting, which assumes Gaussian errors.

XRT spectra [0.3-10 keV] were extracted from circular regions (25-arcsec) around the source center and background regions (50 arcsec) away from the source, grouped such that the source spectrum contained at least 1 count per bin. The spectra were fitted with an absorbed power-law model, with the galactic column density ($N_H = 2.4 \times 10^{20} \text{ cm}^{-2}$) (Dickey & Lockman 1990) fixed, using the TBabs model of Wilms, Allen & McCray(2001), leaving only the photon index and the normalization as free parameters. Spectra were fit in the 0.3 to 10.0 keV energy range. Using the photon index from the fitting and the normalization, the spectral model used for fitting is defined as `tbabs*powerlaw`, where `tbabs` represents the Tübingen-Boulder absorption model, accounting for interstellar photoelectric absorption characterized by the neutral hydrogen column density (N_H), while `powerlaw` describes the X-ray emission as a simple power-law function.

The best-fit photon indices for the three source spectra within the first day were $\Gamma = 1.99 \pm 0.23$, $\Gamma = 2.15 \pm 0.15$, and $\Gamma = 1.87 \pm 0.18$, respectively. The corresponding flux at 2 keV was $2.75 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, $8.51 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, and $6.53 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, obtained from the fitted spectral parameters.

Appendix D: Optical Observations

Appendix D.1: Optical Observations

In this section, we detail observations for GRB 250129A by GRANDMA and its associated partners. Early observations of the

optical afterglow of GRB 250129A started on MJD 60704.20 using the TAROT-TCA and TAROT-TCH⁷ telescopes, two robotic 25 cm aperture telescopes located at the Calern Observatory (Observatoire de la Côte d'Azur) and La Silla Observatory, respectively, detected the afterglow at $T - T_0 = 106$ s.

The full observational campaign lasted 24.23 days. We use for this work the data obtained in g' , r' , i' , z' , B , V , R , I bands for extracting the physical properties of the event. We provide in Table D.1 a list of all the telescopes involved in the observational campaign, including the start and end times (relative to T_0) of the first and last observations made by each telescope. We also provide the filters/bands used during the entire campaign. Below, we provide details on all the telescopes that are involved in this study.

The telescopes that contributed to this campaign are as follows: AbAO T-70 Telescope at Abastumani Observatory in Georgia, the ground-based ARTEMIS telescope of the SPECULOOS Northern Observatory (SNO) in Spain, Colibri at San Pedro Martir, C2PU at Calern observatory, Euler telescope at La Silla, FRAM-Augur telescope at Pierre Auger observatory in Argentina, KAIT telescope at Lick Observatory in California, KAO at Kottamia Observatory in Egypt, T193/MISTRAL at Haute-Provence Observatory in France, NAO-2m at Rozhen National Astronomical Observatory in Bulgaria, OPD-0.6m at the Pico dos Dias's Observatory in Brazil, Pic du Midi 1-m Telescope at Pic du Midi observatory in France, Skynet Network, TAROT-TCA located at the Calern observatory in France, TAROT-TCH located at La Silla, TNOT telescope located at the Nanshan Station of Xinjiang Astronomy Observatory in China, YAHPT/AST3-3. Our preliminary results were reported publicly through the General Coordinates Network (GCN)⁸ by (Antier et al. 2025), (Akl et al. 2025b), Watson et al. (2025a), Akl et al. (2025a), Schlek et al. (2025a) and Schlek et al. (2025b).

KNC– In addition to the professional network, GRANDMA activated its Kilonova-Catcher (KNC) citizen science program for further observations with amateurs' telescopes. Seven amateur telescopes observed GRB 250129A, including nicknames Monaterrenti, CAT, MLC, AITP, T11, T30, CH!CMOS, and CDK. Overall, the KNC telescopes started observing from $T - T_0 = 0.857$ days up to $T - T_0 = 3.108$ days. Photometry of KNC images followed the same methodology detailed in Section 2.3.

Abastumani T-70– AbAO T-70 Telescope at Abastumani Observatory in Georgia, with the main mirror diameter of 100 cm located on the Mt. Kanobili (altitude 1610 m above sea level; 41° 45' 17" N, 42° 49' 20" E) and equipped with a p14240-ccd-camera-back-illum-63-5mm-shutter-grade-1 with BVR_cI_c filters provides an FOV of 30', with a readout of 10 s. The limiting magnitude in the R_c filter with an exposure time of 1 min is 18.2 mag (AB system, 3σ).

Artemis SPECULOOS-North/Artemis (Burdanov et al. 2022) is a 1.0-m Ritchey-Chrétien telescope located at the Teide Observatory (Tenerife, Spain). It is equipped with a thermoelectrically cooled 2K×2K Andor iKon-L BEX2-DD CCD camera with a pixel scale of 0.35"/pixel and a total FOV of 12' × 12'. SPECULOOS-North is a twin of the SPECULOOS-South (Je-

⁷ <http://tarot.obs-hp.fr/>

⁸ <https://gcn.nasa.gov/>

hin et al. 2018; Delrez et al. 2018; Sebastian et al. 2021) and SAINT-EX (Demory et al. 2020) telescopes. Observations were performed with the SDSS g' , r' , z' filters.

C2PU– C2PU is a two 1.04-meter telescopes facility of Observatoire de la Côte d’Azur located at the Calern observing station in Southern France (longitude : $06^{\circ} 55' 22.7''$ E, latitude : $43^{\circ} 45' 13.2''$ N, elevation : 1274 m above MSL, IAU observatory code : R87)⁹. For this photometric follow-up, the West “Omicron” telescope of C2PU has been used in its $F/3.17$ optical configuration (parabolic prime focus with a three-lens Wynne corrector). The camera used was a QHY600 from QHYCCD (CMOS sensor Sony IMX455 with 9600×6422 pixels of $3.76 \times 3.76 \mu\text{m}$) in binning 2×2 . The resulting plate scale and field-of-view were $0.47''/\text{pixel}$, and $37.6' \times 25.2'$.

COLIBRÍ– COLIBRÍ¹⁰ is a Franco-Mexican fast, robotic 1.3 m telescope located at the Observatorio Astronómico Nacional (OAN) in the Sierra de San Pedro Mártir, Baja California (Basa et al. 2022). COLIBRÍ used the blue channel of the DDRAGO science imager (Langarica et al. 2024) and the OGSE camera.

OGSE is an ON Semi KAF-16803 front-illuminated CCD in an FLI ML 16803 package. The CCD is $4k \times 4k$ with 9 pixels. The pixel scale is $0.20 \text{ arcsec}/\text{pixel}$, and the field is 13.6 arcmin square. OGSE is equipped with a fixed Baader red filter that transmits from 590 to 690 nm. This filter is narrower and redder than the standard SDSS/Pan-STARRS r filter; the color term in the transformation is $-0.10(g - r)$.

DDRAGO is a two-channel image with the blue channel working in g, r, i and the red in z, y (Langarica et al. 2024). During COLIBRÍ observations, the red channel was not available. The blue channel uses a backside-illuminated, deep-depleted e2v 231-84 CCD in a Spectral Instruments 1110S package. The CCD is $4k \times 4k$ with 15 pixels. The pixel scale is $0.38 \text{ arcsec}/\text{pixel}$, and the field is 25.9 arcmin square. All of our observations were performed with the r filter, which closely approximates SDSS/Pan-STARRS r ; the color term in the transformation is smaller than $0.01(g - r)$.

Euler– The 1.2-metre Euler Telescope is located at La Silla, built and operated by the Geneva Observatory, Université de Genève, Switzerland. The Euler Telescope is equipped with three complementary instruments: the CORALIE spectrograph, the EulerCam (ECAM), and PISCO, a smaller telescope mounted piggyback on the Euler Telescope.

FRAM-Auger– FRAM-Auger is a fully robotic 30 cm $f/6.8$ telescope located at the Pierre Auger Observatory, Malargue, Argentina. The telescope is equipped with Moravian Instruments G4-16000 CCD, and B, V, R, and I filters, and has a field of view of $60' \times 60'$, with a pixel scale of $0.92''/\text{arcseconds}$ per pixel.

KAIT– The 0.76 m Katzman Automatic Imaging Telescope (KAIT), located at the Lick Observatory, California (as part of the Lick Observatory Supernova Search (LOSS; Filippenko et al. 2001)), observed the field of the GRB 250129A from $T - T_0 = 0.196$ days $T - T_0 = 1.393$ days. Observations were

performed in the *Clear*-band (close to the R band; see Li et al. 2003) with a set of 60 s-exposure images.

KAO– The KAO data presented in this study were acquired using the 1.88-m telescope at the Kottamia Astronomical Observatory (KAO), operated by the National Research Institute of Astronomy and Geophysics (NRIAG), Egypt (Azzam et al. 2010). These observations utilized the Kottamia Faint Imaging Spectro-Polarimeter (KFISP), an instrument capable of imaging, spectroscopy, and polarimetry (Azzam et al. 2022). KFISP is mounted at the Cassegrain focus of the telescope and provides a field of view of approximately $8.2 \times 8.2 \text{ arcmin}$. It is equipped with a 2048×2048 pixel liquid nitrogen-cooled CCD camera integrated within the KFISP optics, yielding a pixel scale of 0.24 arcseconds per pixel.

NAO-2m– NAO-2m denotes the 2-m Ritchey-Chrétien telescope of the Rozhen National Astronomical Observatory, Bulgaria. For the present observations, the telescope was equipped with the multi-mode, two-channel focal reducer FoReRo-2 (Jockers et al. 2000), $2k \times 2k$ Andor iKon-L CCD cameras, and a Sloan set of filters. The gain is $1.0 e^- \text{ ADU}^{-1}$ for the blue channel CCD and $1.1 e^- \text{ ADU}^{-1}$ for the red channel one. For both channels, the pixel size is $0'.497$ on the sky and the field-of-view is $17' \times 17'$. Ten or more frames were acquired of the GRB 250129A field in each of the $g'r'i'$ bands with exposure times of 300 or 600 s.

OHP/MISTRAL– MISTRAL (Multi-purpose InSTRument for Astronomy at Low resolution, Schmitt et al. (2024)) is a Faint Object Spectroscopic Camera mounted at the folded Cassegrain focus of the 1.93 m telescope of the Haute-Provence Observatory (OHP). Present observations were made in the blue mode (400–800 nm) during four observing slots. We used r' and i' -band filters¹¹. The CCD is an ANDOR deep-depletion $2K \times 2K$ CCD camera (iKon-L DZ936N BEX2DD CCD-22031) with 13.5 pixels. The cooling is made by a five-layer Peltier device. The operating temperature is -90°C to -95°C . The dark current is lower than 3 electrons/hour/pixel. More details can be found on the instrument website¹².

Pic Du Midi– Pic du Midi 1-m Telescope at Pic du Midi observatory in France. The telescope is equipped with two cameras. The first one is an ANDOR $2K \times 2K$ CCD camera (iKon-L DZ936) with a spatial sampling of $0.5 \text{ arcsec}/\text{pixel}$. The second camera is a LYTID Siris¹³ InGaAs sensor FPA 640×512 pixels, with a spatial sampling of read-out noise of 5 electrons, operated at 77 K.

Skynet– The Skynet Robotic Telescope Network¹⁴ (Skynet) is a fully automated global network of optical and radio telescopes used for both education and research. Founded and operated out of the University of North Carolina at Chapel Hill, Skynet is comprised of the Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes (PROMPT; Reichart et al. 2005),

¹¹ https://ohp.osupytheas.fr/wp-content/uploads/2025/04/filter_characteristics.html

¹² <https://ohp.osupytheas.fr/mistral-spectro-imager/>

¹³ <https://lytid.com/wp-content/uploads/2024/06/SIRIS-brochure-June-2024.pdf>

¹⁴ <https://skynet.unc.edu/>

⁹ <https://www.oca.eu/fr/c2pu-accueil>

¹⁰ <https://www.colibri-obs.org/>

which were originally dedicated to rapid-response observations of GRBs (Reichart 2006), as well as various other optical telescopes from participating institutions across the globe.

Approximately one minute after the *Swift*-*BAT* trigger time (2025-01-29 4:45:09), Skynet's Campaign Manager software (Dutton et al. 2022) automatically scheduled observations of the field of GRB 250129A on all available Skynet telescopes. The field of the GRB was subsequently observed using the 40 cm PROMPT-2, PROMPT-5 and PROMPT-6 telescopes at the Cerro Tololo Inter-American Observatory, the 40 cm PROMPT-MO-1 telescope at Meckering Observatory, the 40 cm MLC-RCOS16 telescope at the Montana Learning Center, the 50 cm OAUJ-CDK500 telescope at the Astronomical Observatory of the Jagiellonian University, and 40 cm the APUS-CDK24 telescope (Albin 2018) at the American Public University System Observatory.

TNOT– The Tsinghua-Nanshan Optical Telescope, an 80-cm aperture reflector telescope located at Nanshan Station of Xinjiang Astronomy Observatories (XAO), Chinese Academy of Sciences (CAS). The field of view was designed to $26.5'' \times 26.5''$, and the Bessel BV system and Sloan ugri system were chosen as the main filter set. The imaging system utilizes an Andor iKon-L DZ936 CCD camera with a 2048×2048 pixel array, and the pixel scale is 0.78 arc seconds.

YAHPT/AST3-3– The YaoAn High Precision Telescope (YAHPT) is an 80-cm diameter automatic telescope manufactured by ASA and deployed at the YaoAn Astronomical Station in Yunnan Province. Equipped with a PIXIS 2024B camera, it provides a field of view of $11'' \times 11''$ and is dedicated to high-precision astrometric measurements of natural satellites and asteroids. The third Antarctic Survey Telescope (AST3-3, 68 cm Schimdt) was also temporarily deployed at the YaoAn station for commissioning before its final deployment to Dome A, Antarctica. AST3-3 is now equipped with a QHY411 camera featuring a Sony IMX-411 sensor, offering a field of view of $1.65^\circ \times 1.23^\circ$ with a $14\text{K} \times 10\text{K}$ pixel array. The basic data processing for both YAHPT and AST3-3 follows the standard CCDPROC procedures, with astrometric calibration based on the Gaia DR3 catalog.

| Instrument | $T - T_{0start}$ | $T - T_{0end}$ | Bands |
|------------------|------------------|----------------|-----------------------|
| TAROT/TCH | < 0.001 | 0.140 | <i>R</i> |
| FRAM-Auger | 0.008 | 0.090 | <i>R</i> |
| Skynet-PROMPT-5 | 0.019 | 3.165 | <i>B, V, R</i> |
| Skynet-PROMPT-6 | 0.019 | 3.166 | <i>B, V, R, I</i> |
| OHP/MISTRAL | 0.038 | 7.992 | <i>r', i'</i> |
| KAIT | 0.196 | 1.393 | <i>R</i> |
| Skynet-MLC | 0.201 | 0.233 | <i>R</i> |
| TNOT | 0.646 | 4.816 | <i>g', r'</i> |
| Skynet-OUAI | 0.806 | 1.835 | <i>R</i> |
| KAO | 0.847 | 0.874 | <i>g', r', i', z'</i> |
| KNC-Montarrenti | 0.857 | 0.8570 | <i>R, I</i> |
| KNC-AITP | 1.034 | 3.092 | <i>V, g', r', i'</i> |
| Skynet-APUS | 1.061 | 1.128 | <i>R</i> |
| COLIBRI | 1.141 | 24.234 | <i>r'</i> |
| KNC-T11 | 1.317 | 1.329 | <i>R, V</i> |
| KNC-T30 | 1.529 | - | <i>R</i> |
| AbAO-T70 | 1.730 | 2.767 | <i>R</i> |
| KNC-CH!CMOS | 2.126 | 3.108 | <i>g', r'</i> |
| Skynet-PROMPT-MO | 2.500 | 2.507 | <i>R</i> |
| Skynet-PROMPT-2 | 3.011 | 3.168 | <i>I</i> |
| KNC-CDK | 3.018 | - | <i>V</i> |
| Euler | 3.115 | 10.158 | <i>R, i'</i> |
| AST3-3 | 3.648 | 4.573 | <i>g'</i> |
| YAHPT | 3.571 | 4.595 | <i>I</i> |
| NAO-2m | 4.884 | 4.951 | <i>g', r', i'</i> |
| T-CAT | 5.836 | - | <i>V, g', r'</i> |
| C2PU | 5.884 | 5.970 | <i>g', r', i', z'</i> |
| Artemis | 6.009 | 7.039 | <i>g', r', z'</i> |
| PicDuMidi-T1M | 6.994 | 7.885 | <i>g', r', J</i> |
| OPD-T60 | 8.100 | 22.049 | <i>R, I</i> |

Table D.1. All observational instruments whose data have been analyzed and incorporated into the results presented in this study. The $T - T_0$ provided is in days.

Table D.2. X-ray data used in this work. "Delay" is the time interval between the start of the observation (T_{start}) and the Swift GRB trigger time (2025-01-29T04:45:09). We display both the unabsorbed flux densities and the corresponding computed AB magnitudes.

| T_{start} | | Delay | | Band | Flux | | | Instrument |
|---------------------|-----------|--------|--------|-------------------|------------------|--------------------------|-------------------|------------|
| UT | MJD | (day) | (s) | Central frequency | AB Magnitude | Flux density (μ Jy) | Error (μ Jy) | |
| X-ray bands | | | | | | | | |
| 2025-01-29T05:04:53 | 60704.212 | 0.014 | 1185 | 2keV | 24.27 ± 0.24 | 0.711 | 0.16 | Swift XRT |
| 2025-01-29T05:06:32 | 60704.213 | 0.015 | 1284 | 2keV | 24.14 ± 0.24 | 0.804 | 0.18 | Swift XRT |
| 2025-01-29T05:08:05 | 60704.214 | 0.016 | 1376 | 2keV | 23.76 ± 0.25 | 1.140 | 0.26 | Swift XRT |
| 2025-01-29T05:10:00 | 60704.215 | 0.017 | 1491 | 2keV | 23.88 ± 0.24 | 1.019 | 0.23 | Swift XRT |
| 2025-01-29T05:11:54 | 60704.217 | 0.019 | 1605 | 2keV | 24.02 ± 0.25 | 0.896 | 0.20 | Swift XRT |
| 2025-01-29T05:14:10 | 60704.218 | 0.020 | 1742 | 2keV | 24.23 ± 0.25 | 0.741 | 0.17 | Swift XRT |
| 2025-01-29T05:16:28 | 60704.220 | 0.022 | 1879 | 2keV | 24.14 ± 0.21 | 0.802 | 0.16 | Swift XRT |
| 2025-01-29T06:16:42 | 60704.262 | 0.064 | 5493 | 2keV | 24.65 ± 0.23 | 0.503 | 0.10 | Swift XRT |
| 2025-01-29T07:53:25 | 60704.329 | 0.131 | 11297 | 2keV | 24.99 ± 0.23 | 0.367 | 0.08 | Swift XRT |
| 2025-01-29T09:23:47 | 60704.392 | 0.194 | 16719 | 2keV | 24.64 ± 0.28 | 0.505 | 0.13 | Swift XRT |
| 2025-01-29T11:04:33 | 60704.461 | 0.263 | 22765 | 2keV | 24.39 ± 0.23 | 0.637 | 0.13 | Swift XRT |
| 2025-01-29T12:41:03 | 60704.529 | 0.330 | 28554 | 2keV | 24.80 ± 0.25 | 0.436 | 0.10 | Swift XRT |
| 2025-01-29T14:09:34 | 60704.590 | 0.392 | 33865 | 2keV | 25.24 ± 0.31 | 0.292 | 0.08 | Swift XRT |
| 2025-01-30T05:41:43 | 60705.237 | 1.039 | 89795 | 2keV | 27.52 ± 0.20 | 0.036 | 0.01 | Swift XRT |
| 2025-02-01T02:16:30 | 60707.095 | 2.897 | 250281 | 2keV | 28.92 ± 0.23 | 0.010 | 0.00 | Swift XRT |
| 2025-02-05T20:07:18 | 60711.838 | 7.640 | 660130 | 2keV | 30.77 ± 0.33 | 0.002 | 0.00 | Swift XRT |
| 2025-02-09T12:25:46 | 60715.518 | 11.320 | 978038 | 2keV | 31.41 ± 0.51 | 0.001 | 0.00 | Swift XRT |

Table D.3. UVOIR observations of GRB 250129A. In column (2), $T_{(s)}$ is the time delay between the start of the observation and the Swift GRB trigger time (2025-01-29T04:45:09), all in days. Column (4) gives apparent magnitudes or 5- σ upper-limits in the AB system, without any correction. In Column (7), a cross means we did use this data point for the Bayesian analysis.

| T_{start} | | $T - T_{GRB}$ | | Filter | Magnitude | Corrected Magnitude | Telescope | Analysis |
|---------------------|-----------|---------------|----------|--------------|------------------|---------------------|-------------|----------|
| UT | MJD | Day | Minute | (3) | (4) | (5) | (6) | (7) |
| <i>uv</i> band | | | | | | | | |
| 2025-01-29T04:47:42 | 60704.200 | 0.002 | 2.557 | <i>v</i> | 17.58 ± 0.45 | 17.48 ± 0.45 | <i>UVOT</i> | x |
| 2025-01-29T05:06:08 | 60704.213 | 0.015 | 20.987 | <i>white</i> | 18.19 ± 0.06 | 18.04 ± 0.06 | <i>UVOT</i> | |
| 2025-01-29T05:07:41 | 60704.214 | 0.016 | 22.535 | <i>v</i> | 16.73 ± 0.21 | 16.64 ± 0.21 | <i>UVOT</i> | x |
| 2025-01-29T05:09:21 | 60704.215 | 0.017 | 24.216 | <i>b</i> | 17.10 ± 0.17 | 16.97 ± 0.17 | <i>UVOT</i> | x |
| 2025-01-29T05:09:46 | 60704.215 | 0.017 | 24.625 | <i>white</i> | 18.14 ± 0.10 | 17.99 ± 0.10 | <i>UVOT</i> | |
| 2025-01-29T05:09:58 | 60704.215 | 0.017 | 24.828 | <i>uvw1</i> | 19.55 ± 0.35 | 19.34 ± 0.35 | <i>UVOT</i> | |
| 2025-01-29T05:10:23 | 60704.216 | 0.018 | 25.242 | <i>u</i> | 18.03 ± 0.14 | 17.87 ± 0.14 | <i>UVOT</i> | x |
| 2025-01-29T05:10:35 | 60704.216 | 0.018 | 25.449 | <i>v</i> | 16.97 ± 0.27 | 16.88 ± 0.27 | <i>UVOT</i> | x |
| 2025-01-29T05:12:15 | 60704.217 | 0.019 | 27.112 | <i>b</i> | 16.86 ± 0.16 | 16.73 ± 0.16 | <i>UVOT</i> | x |
| 2025-01-29T05:12:39 | 60704.217 | 0.019 | 27.516 | <i>white</i> | 18.17 ± 0.12 | 18.01 ± 0.12 | <i>UVOT</i> | |
| 2025-01-29T05:15:07 | 60704.219 | 0.021 | 29.983 | <i>b</i> | 17.25 ± 0.23 | 17.13 ± 0.23 | <i>UVOT</i> | x |
| 2025-01-29T05:15:33 | 60704.219 | 0.021 | 30.407 | <i>white</i> | 18.10 ± 0.12 | 17.95 ± 0.12 | <i>UVOT</i> | |
| 2025-01-29T05:15:45 | 60704.219 | 0.021 | 30.609 | <i>uvw1</i> | 19.36 ± 0.36 | 19.15 ± 0.36 | <i>UVOT</i> | |
| 2025-01-29T05:15:58 | 60704.219 | 0.021 | 30.829 | <i>uvw2</i> | >21.06 | >20.81 | <i>UVOT</i> | |
| 2025-01-29T05:16:09 | 60704.220 | 0.022 | 31.012 | <i>u</i> | 17.76 ± 0.16 | 17.61 ± 0.16 | <i>UVOT</i> | x |
| 2025-01-29T05:16:23 | 60704.220 | 0.022 | 31.246 | <i>v</i> | 17.45 ± 0.44 | 17.36 ± 0.44 | <i>UVOT</i> | x |
| 2025-01-29T06:11:33 | 60704.258 | 0.060 | 86.405 | <i>b</i> | 17.56 ± 0.32 | 17.43 ± 0.32 | <i>UVOT</i> | x |
| 2025-01-29T06:14:13 | 60704.260 | 0.062 | 89.080 | <i>b</i> | 17.56 ± 0.06 | 17.43 ± 0.06 | <i>UVOT</i> | x |
| 2025-01-29T06:17:38 | 60704.262 | 0.064 | 92.492 | <i>white</i> | 18.42 ± 0.06 | 18.27 ± 0.06 | <i>UVOT</i> | |
| 2025-01-29T07:56:09 | 60704.331 | 0.133 | 191.002 | <i>v</i> | 17.97 ± 0.08 | 17.87 ± 0.08 | <i>UVOT</i> | x |
| 2025-01-29T09:24:31 | 60704.392 | 0.194 | 279.381 | <i>b</i> | 17.48 ± 0.06 | 17.35 ± 0.06 | <i>UVOT</i> | x |
| 2025-01-29T11:00:21 | 60704.459 | 0.261 | 375.207 | <i>uvm2</i> | >24.78 | >24.52 | <i>UVOT</i> | |
| 2025-01-29T11:11:42 | 60704.466 | 0.268 | 386.551 | <i>uvw1</i> | 20.14 ± 0.13 | 19.93 ± 0.13 | <i>UVOT</i> | |
| 2025-01-29T12:34:14 | 60704.524 | 0.326 | 469.097 | <i>u</i> | 18.42 ± 0.06 | 18.27 ± 0.06 | <i>UVOT</i> | x |
| 2025-01-29T12:49:19 | 60704.534 | 0.336 | 484.179 | <i>b</i> | 18.05 ± 0.06 | 17.93 ± 0.06 | <i>UVOT</i> | x |
| 2025-01-29T15:42:35 | 60704.655 | 0.457 | 657.449 | <i>uvw1</i> | 21.59 ± 0.28 | 21.38 ± 0.28 | <i>UVOT</i> | |
| 2025-01-29T15:57:33 | 60704.665 | 0.467 | 672.403 | <i>u</i> | 19.20 ± 0.06 | 19.05 ± 0.06 | <i>UVOT</i> | x |
| 2025-01-29T18:47:18 | 60704.783 | 0.585 | 842.152 | <i>b</i> | 19.03 ± 0.18 | 18.91 ± 0.18 | <i>UVOT</i> | x |
| 2025-01-30T02:50:30 | 60705.118 | 0.920 | 1325.356 | <i>u</i> | 20.08 ± 0.17 | 19.92 ± 0.17 | <i>UVOT</i> | x |
| 2025-01-30T02:55:56 | 60705.122 | 0.924 | 1330.799 | <i>white</i> | 20.57 ± 0.13 | 20.42 ± 0.13 | <i>UVOT</i> | |
| 2025-01-30T03:04:06 | 60705.128 | 0.930 | 1338.952 | <i>v</i> | 19.20 ± 0.32 | 19.11 ± 0.32 | <i>UVOT</i> | x |
| 2025-01-30T12:18:01 | 60705.513 | 1.314 | 1892.873 | <i>white</i> | 20.48 ± 0.13 | 20.33 ± 0.13 | <i>UVOT</i> | |
| 2025-01-31T10:02:37 | 60706.418 | 2.220 | 3197.471 | <i>white</i> | 21.17 ± 0.12 | 21.01 ± 0.12 | <i>UVOT</i> | |
| 2025-01-31T21:02:59 | 60706.877 | 2.679 | 3857.843 | <i>white</i> | 21.16 ± 0.13 | 21.01 ± 0.13 | <i>UVOT</i> | |

| T_{start} UT | MJD | $T - T_{\text{GRB}}$ Day Minute | | Filter | Magnitude | Corrected Magnitude | Telescope | Analysis |
|--------------------------|-----------|------------------------------------|-----------|--------------|------------|---------------------|---------------|----------|
| (1) | | (2) | | (3) | (4) | (5) | (6) | (7) |
| 2025-02-01T16:00:20 | 60707.667 | 3.469 | 4995.193 | <i>white</i> | 21.38±0.12 | 21.23±0.12 | <i>UVOT</i> | |
| 2025-02-01T19:48:07 | 60707.825 | 3.627 | 5222.977 | <i>white</i> | 21.81±0.16 | 21.66±0.16 | <i>UVOT</i> | |
| 2025-02-01T20:43:07 | 60707.863 | 3.665 | 5277.967 | <i>white</i> | >23.00 | >22.85 | <i>UVOT</i> | |
| 2025-02-06T13:16:46 | 60712.553 | 8.355 | 12031.617 | <i>u</i> | 22.61±0.36 | 22.46±0.36 | <i>UVOT</i> | x |
| 2025-02-09T13:15:24 | 60715.552 | 11.354 | 16350.256 | <i>uvw1</i> | >23.00 | 22.79 | <i>UVOT</i> | |
| 2025-02-10T21:34:48 | 60716.899 | 12.701 | 18289.663 | <i>u</i> | 22.32±0.35 | 22.17±0.35 | <i>UVOT</i> | x |
| <i>B</i> band | | | | | | | | |
| 2025-01-29T05:13:55 | 60704.218 | 0.020 | 28.770 | <i>B</i> | 17.27±0.07 | 17.14±0.07 | Skynet | x |
| 2025-01-29T05:16:31 | 60704.220 | 0.022 | 31.376 | <i>B</i> | 17.23±0.05 | 17.11±0.05 | Skynet | x |
| 2025-01-29T05:20:13 | 60704.222 | 0.024 | 35.077 | <i>B</i> | 17.30±0.06 | 17.18±0.06 | Skynet | x |
| 2025-01-29T05:26:09 | 60704.227 | 0.028 | 41.010 | <i>B</i> | 17.34±0.04 | 17.21±0.04 | Skynet | x |
| 2025-01-29T05:27:38 | 60704.228 | 0.030 | 42.493 | <i>B</i> | 17.29±0.04 | 17.16±0.04 | Skynet | x |
| 2025-01-29T05:35:46 | 60704.233 | 0.035 | 50.629 | <i>B</i> | 17.39±0.04 | 17.26±0.04 | Skynet | x |
| 2025-01-29T05:36:01 | 60704.233 | 0.035 | 50.874 | <i>B</i> | 17.27±0.04 | 17.14±0.04 | Skynet | x |
| 2025-01-29T05:45:38 | 60704.240 | 0.042 | 60.493 | <i>B</i> | 17.40±0.04 | 17.27±0.04 | Skynet | x |
| 2025-01-29T05:47:59 | 60704.242 | 0.044 | 62.840 | <i>B</i> | 17.47±0.03 | 17.34±0.03 | Skynet | x |
| 2025-01-29T05:56:54 | 60704.248 | 0.050 | 71.754 | <i>B</i> | 17.39±0.03 | 17.26±0.03 | Skynet | x |
| 2025-01-29T06:02:16 | 60704.252 | 0.054 | 77.125 | <i>B</i> | 17.44±0.03 | 17.32±0.03 | Skynet | x |
| 2025-01-29T06:10:05 | 60704.257 | 0.059 | 84.944 | <i>B</i> | 17.44±0.04 | 17.32±0.04 | Skynet | x |
| 2025-01-29T06:18:39 | 60704.263 | 0.065 | 93.512 | <i>B</i> | 17.59±0.03 | 17.47±0.03 | Skynet | x |
| 2025-01-29T06:29:53 | 60704.271 | 0.073 | 104.744 | <i>B</i> | 17.64±0.03 | 17.52±0.03 | Skynet | x |
| 2025-01-29T06:38:09 | 60704.277 | 0.078 | 113.010 | <i>B</i> | 17.66±0.03 | 17.54±0.03 | Skynet | x |
| 2025-01-29T07:51:06 | 60704.327 | 0.129 | 185.960 | <i>B</i> | 18.32±0.06 | 18.20±0.06 | Skynet | x |
| 2025-01-29T08:33:24 | 60704.357 | 0.159 | 228.253 | <i>B</i> | 17.87±0.04 | 17.75±0.04 | Skynet | x |
| <i>g'</i> band | | | | | | | | |
| 2025-01-29T20:15:56 | 60704.844 | 0.646 | 930.783 | <i>g'</i> | 19.21±0.03 | 19.09±0.03 | TNOT | x |
| 2025-01-30T01:05:00 | 60705.045 | 0.847 | 1219.853 | <i>g'</i> | 19.40±0.06 | 19.28±0.06 | KAO | x |
| 2025-01-30T05:53:59 | 60705.246 | 1.048 | 1508.837 | <i>g'</i> | 18.94±0.04 | 18.82±0.04 | KNC | x |
| 2025-01-30T06:04:01 | 60705.253 | 1.055 | 1518.877 | <i>g'</i> | 19.00±0.05 | 18.89±0.05 | KNC | x |
| 2025-01-30T07:28:41 | 60705.312 | 1.114 | 1603.544 | <i>g'</i> | 19.16±0.05 | 19.04±0.05 | KNC | x |
| 2025-01-30T07:50:29 | 60705.327 | 1.129 | 1625.337 | <i>g'</i> | 19.11±0.05 | 18.99±0.05 | KNC | x |
| 2025-01-30T08:00:55 | 60705.334 | 1.136 | 1635.772 | <i>g'</i> | 19.23±0.05 | 19.11±0.05 | KNC | x |
| 2025-01-31T05:39:41 | 60706.236 | 2.038 | 2934.540 | <i>g'</i> | 20.63±0.14 | 20.52±0.14 | KNC | x |
| 2025-01-31T07:52:55 | 60706.328 | 2.130 | 3067.767 | <i>g'</i> | 20.28±0.12 | 20.16±0.12 | KNC | x |
| 2025-02-01T06:37:04 | 60707.276 | 3.078 | 4431.930 | <i>g'</i> | 20.52±0.12 | 20.41±0.12 | KNC | x |
| 2025-02-01T06:57:10 | 60707.290 | 3.092 | 4452.033 | <i>g'</i> | 20.65±0.13 | 20.53±0.13 | KNC | x |
| 2025-02-01T20:18:13 | 60707.846 | 3.648 | 5253.081 | <i>g'</i> | 20.79±0.15 | 20.68±0.15 | KNC | x |
| 2025-02-03T01:57:31 | 60709.082 | 4.884 | 7032.368 | <i>g'</i> | 21.35±0.10 | 21.23±0.10 | NAO-2m | x |
| 2025-02-04T00:48:59 | 60710.034 | 5.836 | 8403.838 | <i>g'</i> | 21.50±0.20 | 21.38±0.20 | KNC | x |
| 2025-02-04T02:42:14 | 60710.113 | 5.915 | 8517.089 | <i>g'</i> | 22.30±0.06 | 22.18±0.06 | C2PU-O | x |
| 2025-02-04T04:58:11 | 60710.207 | 6.009 | 8653.038 | <i>g'</i> | 22.47±0.08 | 22.35±0.08 | Artemis | x |
| 2025-02-05T04:57:09 | 60711.206 | 7.008 | 10092.016 | <i>g'</i> | 22.62±0.09 | 22.50±0.09 | Artemis | x |
| 2025-02-05T05:31:52 | 60711.230 | 7.032 | 10126.717 | <i>g'</i> | 22.60±0.25 | 22.48±0.25 | PicduMidi/TIM | x |
| <i>V</i> band | | | | | | | | |
| 2025-01-29T05:14:45 | 60704.219 | 0.021 | 29.605 | <i>V</i> | 17.02±0.04 | 16.93±0.04 | Skynet | x |
| 2025-01-29T05:17:36 | 60704.221 | 0.023 | 32.456 | <i>V</i> | 16.96±0.03 | 16.86±0.03 | Skynet | x |
| 2025-01-29T05:21:19 | 60704.223 | 0.025 | 36.172 | <i>V</i> | 17.01±0.04 | 16.92±0.04 | Skynet | x |
| 2025-01-29T05:27:42 | 60704.228 | 0.030 | 42.551 | <i>V</i> | 17.03±0.03 | 16.93±0.03 | Skynet | x |
| 2025-01-29T05:28:57 | 60704.228 | 0.030 | 43.804 | <i>V</i> | 17.00±0.03 | 16.91±0.03 | Skynet | x |
| 2025-01-29T05:37:33 | 60704.234 | 0.036 | 52.415 | <i>V</i> | 17.07±0.03 | 16.98±0.03 | Skynet | x |
| 2025-01-29T05:37:39 | 60704.234 | 0.036 | 52.501 | <i>V</i> | 17.04±0.02 | 16.94±0.02 | Skynet | x |
| 2025-01-29T05:47:28 | 60704.241 | 0.043 | 62.322 | <i>V</i> | 17.13±0.02 | 17.04±0.02 | Skynet | x |
| 2025-01-29T05:50:17 | 60704.243 | 0.045 | 65.144 | <i>V</i> | 17.09±0.02 | 16.99±0.02 | Skynet | x |
| 2025-01-29T05:59:02 | 60704.249 | 0.051 | 73.885 | <i>V</i> | 17.24±0.02 | 17.15±0.02 | Skynet | x |
| 2025-01-29T06:05:07 | 60704.254 | 0.056 | 79.976 | <i>V</i> | 17.26±0.02 | 17.17±0.02 | Skynet | x |
| 2025-01-29T06:12:37 | 60704.259 | 0.061 | 87.479 | <i>V</i> | 17.25±0.02 | 17.16±0.02 | Skynet | x |
| 2025-01-29T06:22:06 | 60704.265 | 0.067 | 96.954 | <i>V</i> | 17.34±0.02 | 17.25±0.02 | Skynet | x |
| 2025-01-29T06:32:59 | 60704.273 | 0.075 | 107.840 | <i>V</i> | 17.45±0.02 | 17.36±0.02 | Skynet | x |
| 2025-01-29T06:42:17 | 60704.279 | 0.081 | 117.143 | <i>V</i> | 17.51±0.02 | 17.42±0.02 | Skynet | x |
| 2025-01-29T07:56:15 | 60704.331 | 0.133 | 191.116 | <i>V</i> | 18.01±0.04 | 17.92±0.04 | Skynet | x |
| 2025-01-29T08:39:52 | 60704.361 | 0.163 | 234.733 | <i>V</i> | 17.61±0.02 | 17.52±0.02 | Skynet | x |
| 2025-01-30T05:15:39 | 60705.219 | 1.021 | 1470.512 | <i>V</i> | 19.08±0.05 | 18.99±0.05 | Skynet | x |
| 2025-01-30T05:30:51 | 60705.230 | 1.032 | 1485.704 | <i>V</i> | 19.00±0.04 | 18.91±0.04 | Skynet | x |
| 2025-01-30T05:46:04 | 60705.240 | 1.042 | 1500.925 | <i>V</i> | 18.99±0.04 | 18.90±0.04 | Skynet | x |
| 2025-01-30T06:01:16 | 60705.251 | 1.053 | 1516.117 | <i>V</i> | 18.91±0.03 | 18.82±0.03 | Skynet | x |
| 2025-01-30T06:16:28 | 60705.261 | 1.063 | 1531.324 | <i>V</i> | 18.91±0.04 | 18.82±0.04 | Skynet | x |
| 2025-01-30T06:31:39 | 60705.272 | 1.074 | 1546.516 | <i>V</i> | 18.93±0.04 | 18.83±0.04 | Skynet | x |

| T_{start} UT | MJD | $T - T_{GRB}$ Day Minute | | Filter | Magnitude | Corrected Magnitude | Telescope | Analysis |
|--------------------------|-----------|-----------------------------|-----------|-----------|------------|---------------------|---------------|----------|
| (1) | | (2) | | (3) | (4) | (5) | (6) | (7) |
| 2025-01-30T06:46:52 | 60705.283 | 1.085 | 1561.722 | V | 19.04±0.04 | 18.95±0.04 | Skynet | x |
| 2025-01-30T07:02:04 | 60705.293 | 1.095 | 1576.928 | V | 19.17±0.04 | 19.08±0.04 | Skynet | x |
| 2025-01-30T07:17:16 | 60705.304 | 1.106 | 1592.120 | V | 19.28±0.05 | 19.19±0.05 | Skynet | x |
| 2025-01-30T07:32:27 | 60705.314 | 1.116 | 1607.312 | V | 19.23±0.05 | 19.14±0.05 | Skynet | x |
| 2025-01-30T07:45:08 | 60705.323 | 1.125 | 1619.999 | V | 19.27±0.05 | 19.17±0.05 | Skynet | x |
| 2025-01-30T08:02:49 | 60705.335 | 1.137 | 1637.682 | V | 19.26±0.05 | 19.16±0.05 | Skynet | x |
| 2025-01-30T08:18:02 | 60705.346 | 1.148 | 1652.888 | V | 19.23±0.05 | 19.13±0.05 | Skynet | x |
| 2025-01-30T08:35:46 | 60705.358 | 1.160 | 1670.629 | V | 19.20±0.04 | 19.10±0.04 | Skynet | x |
| 2025-02-01T05:56:31 | 60707.248 | 3.050 | 4391.380 | V | 20.94±0.07 | 20.85±0.07 | Skynet | x |
| 2025-02-01T07:47:57 | 60707.325 | 3.127 | 4502.807 | V | 21.17±0.07 | 21.08±0.07 | Skynet | x |
| <i>r'</i> band | | | | | | | | |
| 2025-01-29T20:34:41 | 60704.857 | 0.659 | 949.550 | <i>r'</i> | 18.96±0.05 | 18.88±0.05 | TNOT | x |
| 2025-01-30T01:17:48 | 60705.054 | 0.856 | 1232.666 | <i>r'</i> | 19.17±0.05 | 19.09±0.05 | KAO | x |
| 2025-01-30T06:14:06 | 60705.260 | 1.062 | 1528.956 | <i>r'</i> | 18.71±0.06 | 18.63±0.06 | KNC | x |
| 2025-01-30T07:40:07 | 60705.320 | 1.122 | 1614.977 | <i>r'</i> | 18.90±0.05 | 18.82±0.05 | KNC | x |
| 2025-01-30T08:08:34 | 60705.339 | 1.141 | 1643.425 | <i>r'</i> | 18.96±0.03 | 18.88±0.03 | COLIBRI-VIS | x |
| 2025-01-30T09:22:49 | 60705.391 | 1.193 | 1717.681 | <i>r'</i> | 18.99±0.04 | 18.91±0.04 | COLIBRI-VIS | x |
| 2025-01-30T11:30:56 | 60705.480 | 1.282 | 1845.797 | <i>r'</i> | 19.22±0.03 | 19.14±0.03 | COLIBRI-VIS | x |
| 2025-01-31T05:49:56 | 60706.243 | 2.045 | 2944.787 | <i>r'</i> | 19.94±0.12 | 19.86±0.12 | KNC | x |
| 2025-01-31T08:08:01 | 60706.339 | 2.141 | 3082.871 | <i>r'</i> | 20.33±0.05 | 20.25±0.05 | COLIBRI-VIS | x |
| 2025-01-31T08:24:30 | 60706.350 | 2.152 | 3099.361 | <i>r'</i> | 20.47±0.08 | 20.39±0.08 | COLIBRI-VIS | x |
| 2025-01-31T10:16:49 | 60706.428 | 2.230 | 3211.681 | <i>r'</i> | 20.71±0.09 | 20.63±0.09 | COLIBRI-VIS | x |
| 2025-01-31T11:59:50 | 60706.500 | 2.302 | 3314.691 | <i>r'</i> | 20.51±0.05 | 20.43±0.05 | COLIBRI-VIS | x |
| 2025-02-01T07:21:03 | 60707.306 | 3.108 | 4475.900 | <i>r'</i> | 20.43±0.10 | 20.35±0.10 | KNC | x |
| 2025-02-01T08:34:39 | 60707.357 | 3.159 | 4549.501 | <i>r'</i> | 20.52±0.06 | 20.45±0.06 | COLIBRI-VIS | x |
| 2025-02-01T11:29:39 | 60707.479 | 3.281 | 4724.515 | <i>r'</i> | 20.56±0.05 | 20.48±0.05 | COLIBRI-VIS | x |
| 2025-02-02T08:05:45 | 60708.337 | 4.139 | 5960.601 | <i>r'</i> | 21.45±0.20 | 21.37±0.20 | COLIBRI-VIS | x |
| 2025-02-02T12:00:15 | 60708.500 | 4.302 | 6195.103 | <i>r'</i> | 21.53±0.12 | 21.45±0.12 | COLIBRI-VIS | x |
| 2025-02-03T03:34:41 | 60709.149 | 4.951 | 7129.546 | <i>r'</i> | 21.86±0.07 | 21.78±0.07 | NAO-2m | x |
| 2025-02-03T04:40:51 | 60709.195 | 4.997 | 7195.706 | <i>r'</i> | 21.76±0.14 | 21.68±0.14 | OHP/MISTRAL | x |
| 2025-02-03T08:11:50 | 60709.342 | 5.144 | 7406.689 | <i>r'</i> | 21.87±0.10 | 21.79±0.10 | COLIBRI-VIS | x |
| 2025-02-03T12:00:38 | 60709.500 | 5.302 | 7635.497 | <i>r'</i> | 21.99±0.10 | 21.91±0.10 | COLIBRI-VIS | x |
| 2025-02-04T05:20:12 | 60710.222 | 6.024 | 8675.057 | <i>r'</i> | 22.19±0.10 | 22.11±0.10 | Artemis | x |
| 2025-02-04T07:34:16 | 60710.315 | 6.117 | 8809.120 | <i>r'</i> | 22.36±0.17 | 22.28±0.17 | COLIBRI-VIS | x |
| 2025-02-05T04:36:52 | 60711.192 | 6.994 | 10071.733 | <i>r'</i> | 22.50±0.11 | 22.42±0.11 | PicduMidi/T1M | x |
| 2025-02-05T05:18:36 | 60711.221 | 7.023 | 10113.455 | <i>r'</i> | 22.27±0.09 | 22.19±0.09 | Artemis | x |
| 2025-02-05T10:31:09 | 60711.438 | 7.240 | 10426.002 | <i>r'</i> | 22.44±0.10 | 22.36±0.10 | COLIBRI-VIS | x |
| 2025-02-06T01:59:45 | 60712.083 | 7.885 | 11354.606 | <i>r'</i> | 22.34±0.14 | 22.26±0.14 | PicduMidi/T1M | x |
| 2025-02-06T10:59:27 | 60712.458 | 8.260 | 11894.302 | <i>r'</i> | 22.44±0.07 | 22.36±0.07 | COLIBRI-VIS | x |
| 2025-02-07T10:58:37 | 60713.457 | 9.259 | 13333.474 | <i>r'</i> | 22.70±0.12 | 22.62±0.12 | COLIBRI-VIS | x |
| 2025-02-08T10:01:36 | 60714.418 | 10.220 | 14716.456 | <i>r'</i> | 22.78±0.10 | 22.70±0.10 | COLIBRI-VIS | x |
| 2025-02-09T10:00:12 | 60715.417 | 11.219 | 16155.065 | <i>r'</i> | 22.68±0.10 | 22.60±0.10 | COLIBRI-VIS | x |
| 2025-02-10T10:03:01 | 60716.419 | 12.221 | 17597.879 | <i>r'</i> | 23.04±0.13 | >22.96±0.13 | COLIBRI-VIS | x |
| 2025-02-19T11:18:58 | 60725.472 | 21.273 | 30633.824 | <i>r'</i> | 23.50±0.09 | 23.42±0.09 | COLIBRI-VIS | x |
| 2025-02-22T10:21:21 | 60728.431 | 24.233 | 34896.206 | <i>r'</i> | 23.71±0.10 | 23.63±0.10 | COLIBRI-VIS | x |
| <i>R</i> band | | | | | | | | |
| 2025-01-29T04:47:00 | 60704.199 | 0.001 | 1.866 | <i>R</i> | >17.49± | >17.42± | TAROT/TCH | x |
| 2025-01-29T04:47:12 | 60704.199 | 0.001 | 2.067 | <i>R</i> | >17.32± | >17.25± | TAROT/TCH | x |
| 2025-01-29T04:47:25 | 60704.200 | 0.002 | 2.267 | <i>R</i> | 16.92±0.40 | 16.85±0.40 | TAROT/TCH | x |
| 2025-01-29T04:47:37 | 60704.200 | 0.002 | 2.467 | <i>R</i> | 17.12±0.40 | 17.05±0.40 | TAROT/TCH | x |
| 2025-01-29T04:47:49 | 60704.200 | 0.002 | 2.667 | <i>R</i> | 16.92±0.40 | 16.85±0.40 | TAROT/TCH | x |
| 2025-01-29T04:48:59 | 60704.201 | 0.003 | 3.844 | <i>R</i> | 17.35±0.16 | 17.27±0.16 | TAROT/TCH | x |
| 2025-01-29T04:49:40 | 60704.201 | 0.003 | 4.520 | <i>R</i> | 17.71±0.23 | 17.63±0.23 | TAROT/TCH | x |
| 2025-01-29T04:50:19 | 60704.202 | 0.004 | 5.168 | <i>R</i> | 18.24±0.37 | 18.16±0.37 | TAROT/TCH | x |
| 2025-01-29T04:50:58 | 60704.202 | 0.004 | 5.831 | <i>R</i> | 18.12±0.32 | 18.04±0.32 | TAROT/TCH | x |
| 2025-01-29T04:52:21 | 60704.203 | 0.005 | 7.213 | <i>R</i> | 17.58±0.12 | 17.50±0.12 | TAROT/TCH | x |
| 2025-01-29T04:54:01 | 60704.204 | 0.006 | 8.869 | <i>R</i> | 17.66±0.13 | 17.59±0.13 | TAROT/TCH | x |
| 2025-01-29T04:55:40 | 60704.205 | 0.007 | 10.525 | <i>R</i> | 17.45±0.10 | 17.38±0.10 | TAROT/TCH | x |
| 2025-01-29T04:56:53 | 60704.206 | 0.008 | 11.735 | <i>R</i> | 17.20±0.14 | 17.13±0.14 | FRAM-Auger | x |
| 2025-01-29T04:57:50 | 60704.207 | 0.009 | 12.700 | <i>R</i> | 17.16±0.08 | 17.09±0.08 | TAROT/TCH | x |
| 2025-01-29T04:59:30 | 60704.208 | 0.010 | 14.356 | <i>R</i> | 17.02±0.07 | 16.95±0.07 | TAROT/TCH | x |
| 2025-01-29T05:01:09 | 60704.209 | 0.011 | 16.012 | <i>R</i> | 17.06±0.07 | 16.99±0.07 | TAROT/TCH | x |
| 2025-01-29T05:02:49 | 60704.210 | 0.012 | 17.668 | <i>R</i> | 16.79±0.09 | 16.71±0.09 | FRAM-Auger | x |
| 2025-01-29T05:03:39 | 60704.211 | 0.013 | 18.503 | <i>R</i> | 17.02±0.05 | 16.94±0.05 | TAROT/TCH | x |
| 2025-01-29T05:06:48 | 60704.213 | 0.015 | 21.656 | <i>R</i> | 16.93±0.04 | 16.85±0.04 | TAROT/TCH | x |
| 2025-01-29T05:08:45 | 60704.214 | 0.016 | 23.600 | <i>R</i> | 16.78±0.07 | 16.70±0.07 | FRAM-Auger | x |
| 2025-01-29T05:09:56 | 60704.215 | 0.017 | 24.796 | <i>R</i> | 16.93±0.05 | 16.86±0.05 | TAROT/TCH | x |

| T_{start} UT (1) | MJD | $T - T_{\text{GRB}}$ Day Minute (2) | | Filter (3) | Magnitude (4) | Corrected Magnitude (5) | Telescope (6) | Analysis (7) |
|---------------------------------|-----------|--|---------|---------------|------------------|----------------------------|------------------|-----------------|
| 2025-01-29T05:13:41 | 60704.218 | 0.020 | 28.540 | R | 16.86±0.07 | 16.79±0.07 | Skynet | x |
| 2025-01-29T05:14:43 | 60704.219 | 0.021 | 29.576 | R | 16.77±0.05 | 16.70±0.05 | Skynet | x |
| 2025-01-29T05:17:01 | 60704.220 | 0.022 | 31.880 | R | 16.81±0.06 | 16.74±0.06 | Skynet | x |
| 2025-01-29T05:20:06 | 60704.222 | 0.024 | 34.962 | R | 16.82±0.06 | 16.75±0.06 | Skynet | x |
| 2025-01-29T05:20:30 | 60704.223 | 0.025 | 35.351 | R | 16.84±0.07 | 16.77±0.07 | FRAM-Auger | x |
| 2025-01-29T05:22:01 | 60704.224 | 0.026 | 36.877 | R | 16.84±0.05 | 16.77±0.05 | Skynet | x |
| 2025-01-29T05:24:00 | 60704.225 | 0.027 | 38.864 | R | 16.79±0.05 | 16.72±0.05 | Skynet | x |
| 2025-01-29T05:24:02 | 60704.225 | 0.027 | 38.893 | R | 16.84±0.04 | 16.77±0.04 | TAROT/TCH | x |
| 2025-01-29T05:26:29 | 60704.227 | 0.029 | 41.341 | R | 16.79±0.04 | 16.72±0.04 | Skynet | x |
| 2025-01-29T05:27:12 | 60704.227 | 0.029 | 42.061 | R | 16.89±0.04 | 16.82±0.04 | TAROT/TCH | x |
| 2025-01-29T05:27:40 | 60704.228 | 0.030 | 42.522 | R | 16.82±0.05 | 16.75±0.05 | Skynet | x |
| 2025-01-29T05:30:21 | 60704.229 | 0.031 | 45.215 | R | 16.87±0.04 | 16.80±0.04 | TAROT/TCH | x |
| 2025-01-29T05:30:57 | 60704.230 | 0.032 | 45.805 | R | 16.80±0.04 | 16.73±0.04 | Skynet | x |
| 2025-01-29T05:31:59 | 60704.231 | 0.033 | 46.842 | R | 16.89±0.04 | 16.82±0.04 | Skynet | x |
| 2025-01-29T05:32:28 | 60704.231 | 0.033 | 47.317 | R | 16.88±0.07 | 16.81±0.07 | FRAM-Auger | x |
| 2025-01-29T05:33:46 | 60704.232 | 0.034 | 48.628 | R | 16.80±0.03 | 16.73±0.03 | TAROT/TCH | x |
| 2025-01-29T05:36:02 | 60704.233 | 0.035 | 50.888 | R | 16.78±0.04 | 16.71±0.04 | Skynet | x |
| 2025-01-29T05:36:16 | 60704.234 | 0.036 | 51.133 | R | 16.87±0.04 | 16.79±0.04 | Skynet | x |
| 2025-01-29T05:36:55 | 60704.234 | 0.036 | 51.781 | R | 16.84±0.03 | 16.77±0.03 | TAROT/TCH | x |
| 2025-01-29T05:40:05 | 60704.236 | 0.038 | 54.935 | R | 16.91±0.03 | 16.83±0.03 | TAROT/TCH | x |
| 2025-01-29T05:40:56 | 60704.237 | 0.039 | 55.799 | R | 16.93±0.04 | 16.86±0.04 | Skynet | x |
| 2025-01-29T05:41:47 | 60704.237 | 0.039 | 56.648 | R | 16.86±0.03 | 16.79±0.03 | Skynet | x |
| 2025-01-29T05:43:31 | 60704.239 | 0.041 | 58.376 | R | 16.94±0.03 | 16.87±0.03 | TAROT/TCH | x |
| 2025-01-29T05:43:31 | 60704.239 | 0.041 | 58.376 | R | 16.92±0.03 | 16.84±0.03 | TAROT/TCH | x |
| 2025-01-29T05:45:57 | 60704.240 | 0.042 | 60.810 | R | 16.89±0.04 | 16.82±0.04 | Skynet | x |
| 2025-01-29T05:47:46 | 60704.242 | 0.043 | 62.624 | R | 16.92±0.03 | 16.85±0.03 | Skynet | x |
| 2025-01-29T05:49:50 | 60704.243 | 0.045 | 64.684 | R | 16.92±0.04 | 16.85±0.04 | TAROT/TCH | x |
| 2025-01-29T05:50:18 | 60704.243 | 0.045 | 65.159 | R | 17.07±0.08 | 17.00±0.08 | FRAM-Auger | x |
| 2025-01-29T05:51:25 | 60704.244 | 0.046 | 66.282 | R | 16.95±0.04 | 16.88±0.04 | Skynet | x |
| 2025-01-29T05:53:20 | 60704.245 | 0.047 | 68.197 | R | 16.93±0.03 | 16.86±0.03 | TAROT/TCH | x |
| 2025-01-29T05:55:52 | 60704.247 | 0.049 | 70.732 | R | 16.98±0.03 | 16.91±0.03 | Skynet | x |
| 2025-01-29T05:56:30 | 60704.248 | 0.050 | 71.365 | R | 16.99±0.03 | 16.91±0.03 | TAROT/TCH | x |
| 2025-01-29T05:57:16 | 60704.248 | 0.050 | 72.128 | R | 16.99±0.04 | 16.92±0.04 | Skynet | x |
| 2025-01-29T05:59:40 | 60704.250 | 0.052 | 74.519 | R | 17.04±0.04 | 16.97±0.04 | TAROT/TCH | x |
| 2025-01-29T06:02:57 | 60704.252 | 0.054 | 77.816 | R | 17.05±0.03 | 16.98±0.03 | TAROT/TCH | x |
| 2025-01-29T06:03:01 | 60704.252 | 0.054 | 77.874 | R | 17.03±0.03 | 16.96±0.03 | Skynet | x |
| 2025-01-29T06:03:40 | 60704.253 | 0.055 | 78.522 | R | 17.07±0.04 | 17.00±0.04 | Skynet | x |
| 2025-01-29T06:06:08 | 60704.254 | 0.056 | 80.984 | R | 17.00±0.04 | 16.92±0.04 | TAROT/TCH | x |
| 2025-01-29T06:07:50 | 60704.255 | 0.057 | 82.684 | R | 17.19±0.08 | 17.12±0.08 | FRAM-Auger | x |
| 2025-01-29T06:09:17 | 60704.256 | 0.058 | 84.138 | R | 17.10±0.04 | 17.03±0.04 | TAROT/TCH | x |
| 2025-01-29T06:10:35 | 60704.257 | 0.059 | 85.434 | R | 17.12±0.04 | 17.05±0.04 | Skynet | x |
| 2025-01-29T06:10:58 | 60704.258 | 0.060 | 85.823 | R | 17.19±0.03 | 17.12±0.03 | Skynet | x |
| 2025-01-29T06:15:51 | 60704.261 | 0.063 | 90.704 | R | 17.15±0.04 | 17.07±0.04 | TAROT/TCH | x |
| 2025-01-29T06:15:51 | 60704.261 | 0.063 | 90.704 | R | 17.07±0.03 | 17.00±0.03 | TAROT/TCH | x |
| 2025-01-29T06:18:00 | 60704.263 | 0.064 | 92.864 | R | 17.24±0.03 | 17.17±0.03 | Skynet | x |
| 2025-01-29T06:19:00 | 60704.263 | 0.065 | 93.858 | R | 17.17±0.04 | 17.10±0.04 | TAROT/TCH | x |
| 2025-01-29T06:19:37 | 60704.264 | 0.066 | 94.477 | R | 17.16±0.03 | 17.09±0.03 | Skynet | x |
| 2025-01-29T06:22:34 | 60704.266 | 0.068 | 97.429 | R | 17.18±0.04 | 17.11±0.04 | TAROT/TCH | x |
| 2025-01-29T06:25:44 | 60704.268 | 0.070 | 100.597 | R | 17.19±0.03 | 17.11±0.03 | TAROT/TCH | x |
| 2025-01-29T06:26:04 | 60704.268 | 0.070 | 100.928 | R | 17.25±0.04 | 17.18±0.04 | Skynet | x |
| 2025-01-29T06:28:54 | 60704.270 | 0.072 | 103.751 | R | 17.18±0.04 | 17.11±0.04 | TAROT/TCH | x |
| 2025-01-29T06:29:08 | 60704.270 | 0.072 | 103.996 | R | 17.26±0.03 | 17.19±0.03 | Skynet | x |
| 2025-01-29T06:31:18 | 60704.272 | 0.074 | 106.156 | R | 17.25±0.08 | 17.18±0.08 | FRAM-Auger | x |
| 2025-01-29T06:34:48 | 60704.274 | 0.076 | 109.655 | R | 17.28±0.03 | 17.21±0.03 | Skynet | x |
| 2025-01-29T06:39:41 | 60704.278 | 0.080 | 114.536 | R | 17.33±0.03 | 17.26±0.03 | Skynet | x |
| 2025-01-29T06:39:57 | 60704.278 | 0.080 | 114.810 | R | 17.30±0.04 | 17.23±0.04 | TAROT/TCH | x |
| 2025-01-29T06:43:07 | 60704.280 | 0.082 | 117.978 | R | 17.37±0.04 | 17.30±0.04 | TAROT/TCH | x |
| 2025-01-29T06:44:15 | 60704.281 | 0.083 | 119.101 | R | 17.35±0.03 | 17.28±0.03 | Skynet | x |
| 2025-01-29T06:46:16 | 60704.282 | 0.084 | 121.132 | R | 17.33±0.04 | 17.25±0.04 | TAROT/TCH | x |
| 2025-01-29T06:54:59 | 60704.288 | 0.090 | 129.844 | R | 17.51±0.10 | 17.43±0.10 | FRAM-Auger | x |
| 2025-01-29T07:17:48 | 60704.304 | 0.106 | 152.653 | R | 17.51±0.04 | 17.44±0.04 | Skynet | x |
| 2025-01-29T07:21:14 | 60704.306 | 0.108 | 156.095 | R | 17.59±0.05 | 17.51±0.05 | TAROT/TCH | x |
| 2025-01-29T07:24:23 | 60704.309 | 0.111 | 159.248 | R | 17.59±0.04 | 17.52±0.04 | TAROT/TCH | x |
| 2025-01-29T07:27:33 | 60704.311 | 0.113 | 162.402 | R | 17.63±0.04 | 17.55±0.04 | TAROT/TCH | x |
| 2025-01-29T07:40:50 | 60704.320 | 0.122 | 175.693 | R | 17.79±0.05 | 17.72±0.05 | TAROT/TCH | x |
| 2025-01-29T07:44:00 | 60704.322 | 0.124 | 178.861 | R | 17.68±0.04 | 17.61±0.04 | TAROT/TCH | x |
| 2025-01-29T07:47:09 | 60704.324 | 0.126 | 182.015 | R | 17.72±0.05 | 17.65±0.05 | TAROT/TCH | x |

| T_{start} UT (1) | MJD | $T - T_{GRB}$ Day Minute (2) | | Filter (3) | Magnitude (4) | Corrected Magnitude (5) | Telescope (6) | Analysis (7) |
|---------------------------------|-----------|---------------------------------------|----------|---------------|------------------|----------------------------|------------------|-----------------|
| 2025-01-29T08:00:14 | 60704.334 | 0.135 | 195.090 | R | 17.87±0.05 | 17.80±0.05 | TAROT/TCH | x |
| 2025-01-29T08:00:16 | 60704.334 | 0.135 | 195.119 | R | 17.94±0.04 | 17.87±0.04 | Skynet | x |
| 2025-01-29T08:03:23 | 60704.336 | 0.138 | 198.244 | R | 17.85±0.05 | 17.77±0.05 | TAROT/TCH | x |
| 2025-01-29T08:06:32 | 60704.338 | 0.140 | 201.397 | R | 17.86±0.05 | 17.79±0.05 | TAROT/TCH | x |
| 2025-01-29T08:44:55 | 60704.365 | 0.167 | 239.773 | R | 17.43±0.02 | 17.36±0.02 | Skynet | x |
| 2025-01-29T09:27:18 | 60704.394 | 0.196 | 282.152 | R | 17.13±0.05 | 17.05±0.05 | KAIT | x |
| 2025-01-29T09:32:03 | 60704.397 | 0.199 | 286.904 | R | 16.78±0.05 | 16.71±0.05 | KAIT | x |
| 2025-01-29T09:36:46 | 60704.401 | 0.203 | 291.628 | R | 16.63±0.05 | 16.56±0.05 | KAIT | x |
| 2025-01-29T09:36:49 | 60704.401 | 0.203 | 291.671 | R | 16.65±0.05 | 16.58±0.05 | Skynet | x |
| 2025-01-29T09:41:31 | 60704.404 | 0.206 | 296.380 | R | 16.48±0.05 | 16.41±0.05 | KAIT | x |
| 2025-01-29T09:46:17 | 60704.407 | 0.209 | 301.146 | R | 16.47±0.05 | 16.40±0.05 | KAIT | x |
| 2025-01-29T09:52:18 | 60704.411 | 0.213 | 307.151 | R | 16.62±0.05 | 16.55±0.05 | Skynet | x |
| 2025-01-29T09:55:49 | 60704.414 | 0.216 | 310.679 | R | 16.45±0.05 | 16.38±0.05 | KAIT | x |
| 2025-01-29T10:00:33 | 60704.417 | 0.219 | 315.402 | R | 16.47±0.05 | 16.40±0.05 | KAIT | x |
| 2025-01-29T10:05:45 | 60704.421 | 0.223 | 320.600 | R | 16.58±0.05 | 16.51±0.05 | KAIT | x |
| 2025-01-29T10:10:28 | 60704.424 | 0.226 | 325.324 | R | 16.71±0.05 | 16.64±0.05 | KAIT | x |
| 2025-01-29T10:12:56 | 60704.426 | 0.228 | 327.786 | R | 16.87±0.06 | 16.80±0.06 | Skynet | x |
| 2025-01-29T10:15:12 | 60704.427 | 0.229 | 330.061 | R | 16.82±0.05 | 16.75±0.05 | KAIT | x |
| 2025-01-29T10:18:06 | 60704.429 | 0.231 | 332.956 | R | 16.92±0.06 | 16.85±0.06 | Skynet | x |
| 2025-01-29T10:20:00 | 60704.431 | 0.233 | 334.856 | R | 16.94±0.05 | 16.87±0.05 | KAIT | x |
| 2025-01-29T10:24:45 | 60704.434 | 0.236 | 339.608 | R | 16.99±0.05 | 16.92±0.05 | KAIT | x |
| 2025-01-29T10:29:32 | 60704.437 | 0.239 | 344.389 | R | 17.03±0.05 | 16.96±0.05 | KAIT | x |
| 2025-01-29T10:34:17 | 60704.440 | 0.242 | 349.141 | R | 17.03±0.05 | 16.96±0.05 | KAIT | x |
| 2025-01-29T10:41:38 | 60704.446 | 0.248 | 356.500 | R | 17.05±0.05 | 16.98±0.05 | KAIT | x |
| 2025-01-29T10:51:22 | 60704.452 | 0.254 | 366.220 | R | 17.09±0.05 | 17.02±0.05 | KAIT | x |
| 2025-01-29T11:00:52 | 60704.459 | 0.261 | 375.724 | R | 17.16±0.05 | 17.09±0.05 | KAIT | x |
| 2025-01-29T11:10:25 | 60704.466 | 0.268 | 385.271 | R | 17.16±0.05 | 17.09±0.05 | KAIT | x |
| 2025-01-29T11:20:06 | 60704.472 | 0.274 | 394.962 | R | 17.20±0.05 | 17.13±0.05 | KAIT | x |
| 2025-01-29T11:29:49 | 60704.479 | 0.281 | 404.682 | R | 17.26±0.05 | 17.19±0.05 | KAIT | x |
| 2025-01-29T11:40:31 | 60704.486 | 0.288 | 415.367 | R | 17.32±0.05 | 17.25±0.05 | KAIT | x |
| 2025-01-29T11:52:31 | 60704.495 | 0.297 | 427.376 | R | 17.38±0.05 | 17.31±0.05 | KAIT | x |
| 2025-01-30T00:20:54 | 60705.015 | 0.816 | 1175.759 | R | 19.17±0.06 | 19.10±0.06 | Skynet | x |
| 2025-01-30T01:03:57 | 60705.044 | 0.846 | 1218.800 | R | 19.26±0.06 | 19.19±0.06 | Skynet | x |
| 2025-01-30T02:36:01 | 60705.108 | 0.910 | 1310.874 | R | 19.28±0.06 | 19.21±0.06 | Skynet | x |
| 2025-01-30T03:14:31 | 60705.135 | 0.937 | 1349.380 | R | 19.32±0.09 | 19.25±0.09 | Skynet | x |
| 2025-01-30T03:50:28 | 60705.160 | 0.962 | 1385.322 | R | 19.30±0.06 | 19.23±0.06 | Skynet | x |
| 2025-01-30T04:16:09 | 60705.178 | 0.980 | 1411.012 | R | 19.46±0.07 | 19.39±0.07 | Skynet | x |
| 2025-01-30T05:30:50 | 60705.230 | 1.032 | 1485.690 | R | 18.71±0.03 | 18.64±0.03 | Skynet | x |
| 2025-01-30T05:45:56 | 60705.240 | 1.042 | 1500.796 | R | 18.71±0.03 | 18.64±0.03 | Skynet | x |
| 2025-01-30T06:31:13 | 60705.272 | 1.074 | 1546.069 | R | 18.82±0.02 | 18.75±0.02 | Skynet | x |
| 2025-01-30T07:01:24 | 60705.293 | 1.095 | 1576.252 | R | 18.93±0.03 | 18.86±0.03 | Skynet | x |
| 2025-01-30T07:46:41 | 60705.324 | 1.126 | 1621.540 | R | 18.99±0.03 | 18.92±0.03 | Skynet | x |
| 2025-01-30T08:34:28 | 60705.357 | 1.159 | 1669.319 | R | 18.88±0.02 | 18.81±0.02 | Skynet | x |
| 2025-01-30T09:22:02 | 60705.390 | 1.192 | 1716.896 | R | 18.86±0.05 | 18.79±0.05 | KAIT | x |
| 2025-01-30T09:39:54 | 60705.403 | 1.205 | 1734.752 | R | 18.97±0.05 | 18.90±0.05 | KAIT | x |
| 2025-01-30T09:58:05 | 60705.415 | 1.217 | 1752.940 | R | 18.99±0.05 | 18.92±0.05 | KAIT | x |
| 2025-01-30T10:15:55 | 60705.428 | 1.230 | 1770.767 | R | 19.03±0.05 | 18.96±0.05 | KAIT | x |
| 2025-01-30T10:34:07 | 60705.440 | 1.242 | 1788.983 | R | 19.03±0.05 | 18.96±0.05 | KAIT | x |
| 2025-01-30T10:52:04 | 60705.453 | 1.255 | 1806.925 | R | 19.06±0.05 | 18.99±0.05 | KAIT | x |
| 2025-01-30T11:10:12 | 60705.465 | 1.267 | 1825.055 | R | 19.09±0.05 | 19.02±0.05 | KAIT | x |
| 2025-01-30T11:28:13 | 60705.478 | 1.280 | 1843.069 | R | 19.11±0.05 | 19.04±0.05 | KAIT | x |
| 2025-01-30T11:46:14 | 60705.490 | 1.292 | 1861.098 | R | 19.16±0.05 | 19.09±0.05 | KAIT | x |
| 2025-01-30T12:04:19 | 60705.503 | 1.305 | 1879.170 | R | 19.21±0.05 | 19.14±0.05 | KAIT | x |
| 2025-01-30T12:22:19 | 60705.516 | 1.317 | 1897.170 | R | 19.28±0.05 | 19.21±0.05 | KAIT | x |
| 2025-01-30T12:40:28 | 60705.528 | 1.330 | 1915.328 | R | 19.24±0.05 | 19.17±0.05 | KAIT | x |
| 2025-01-30T12:58:25 | 60705.541 | 1.343 | 1933.271 | R | 19.38±0.05 | 19.31±0.05 | KAIT | x |
| 2025-01-30T13:16:35 | 60705.553 | 1.355 | 1951.444 | R | 19.42±0.05 | 19.35±0.05 | KAIT | x |
| 2025-01-30T13:16:34 | 60705.553 | 1.355 | 1951.417 | R | 19.43±0.15 | 19.36±0.15 | KNC | x |
| 2025-01-30T13:34:28 | 60705.566 | 1.368 | 1969.328 | R | 19.47±0.05 | 19.40±0.05 | KAIT | x |
| 2025-01-30T13:52:44 | 60705.578 | 1.380 | 1987.588 | R | 19.48±0.05 | 19.41±0.05 | KAIT | x |
| 2025-01-30T14:11:14 | 60705.591 | 1.393 | 2006.092 | R | 19.64±0.05 | 19.57±0.05 | KAIT | x |
| 2025-01-30T17:27:26 | 60705.727 | 1.529 | 2202.300 | R | 19.98±0.15 | 19.90±0.15 | KNC | x |
| 2025-01-30T22:16:50 | 60705.928 | 1.730 | 2491.683 | R | 20.00±0.10 | 19.93±0.10 | AbAO-T70 | x |
| 2025-01-31T05:19:45 | 60706.222 | 2.024 | 2914.602 | R | 20.32±0.06 | 20.25±0.06 | Skynet | x |
| 2025-01-31T06:20:07 | 60706.264 | 2.066 | 2974.967 | R | 20.44±0.07 | 20.37±0.07 | Skynet | x |
| 2025-01-31T07:20:28 | 60706.306 | 2.108 | 3035.332 | R | 20.37±0.07 | 20.30±0.07 | Skynet | x |
| 2025-01-31T08:25:52 | 60706.351 | 2.153 | 3100.722 | R | 20.32±0.06 | 20.25±0.06 | Skynet | x |

| T_{start} UT | MJD | $T - T_{\text{GRB}}$ Day Minute | | Filter | Magnitude | Corrected Magnitude | Telescope | Analysis |
|--------------------------|-----------|---|-----------|-----------|------------|---------------------|-------------|----------|
| (1) | | (2) | | (3) | (4) | (5) | (6) | (7) |
| 2025-01-31T23:10:05 | 60706.965 | 2.767 | 3984.933 | <i>R</i> | 20.44±0.11 | 20.37±0.11 | AbAO-T70 | x |
| 2025-02-01T05:57:27 | 60707.248 | 3.050 | 4392.301 | <i>R</i> | 20.25±0.04 | 20.18±0.04 | Skynet | x |
| 2025-02-01T07:30:44 | 60707.313 | 3.115 | 4485.587 | <i>R</i> | 20.55±0.05 | 20.48±0.05 | Euler | x |
| 2025-02-01T07:48:04 | 60707.325 | 3.127 | 4502.922 | <i>R</i> | 20.49±0.04 | 20.42±0.04 | Skynet | x |
| 2025-02-02T07:20:42 | 60708.306 | 4.108 | 5915.562 | <i>R</i> | 21.06±0.10 | 20.99±0.10 | Euler | x |
| 2025-02-03T08:26:27 | 60709.352 | 5.154 | 7421.317 | <i>R</i> | 21.72±0.10 | 21.65±0.10 | Euler | x |
| 2025-02-05T08:58:33 | 60711.374 | 7.176 | 10333.416 | <i>R</i> | 22.79±0.11 | 22.72±0.11 | Euler | x |
| 2025-02-08T08:09:32 | 60714.340 | 10.142 | 14604.396 | <i>R</i> | 22.81±0.28 | 22.74±0.28 | Euler | x |
| <i>i'</i> band | | | | | | | | |
| 2025-01-29T05:40:14 | 60704.236 | 0.038 | 55.083 | <i>i'</i> | 16.55±0.03 | 16.49±0.03 | OHP/MISTRAL | x |
| 2025-01-30T01:30:37 | 60705.063 | 0.865 | 1245.483 | <i>i'</i> | 18.92±0.03 | 18.86±0.03 | KAO | x |
| 2025-01-30T06:34:13 | 60705.274 | 1.076 | 1549.074 | <i>i'</i> | 18.53±0.11 | 18.48±0.11 | KNC | x |
| 2025-01-30T08:13:54 | 60705.343 | 1.145 | 1648.755 | <i>i'</i> | 18.75±0.12 | 18.69±0.12 | KNC | x |
| 2025-02-01T07:44:08 | 60707.322 | 3.124 | 4498.999 | <i>i'</i> | 20.17±0.05 | 20.11±0.05 | Euler | x |
| 2025-02-02T07:34:06 | 60708.315 | 4.117 | 5928.956 | <i>i'</i> | 21.00±0.06 | 20.94±0.06 | Euler | x |
| 2025-02-03T02:04:30 | 60709.086 | 4.888 | 7039.353 | <i>i'</i> | 21.30±0.10 | 21.24±0.10 | NAO-2m | x |
| 2025-02-03T08:39:54 | 60709.361 | 5.163 | 7434.761 | <i>i'</i> | 21.75±0.10 | 21.69±0.10 | Euler | x |
| 2025-02-04T03:18:10 | 60710.138 | 5.940 | 8553.025 | <i>i'</i> | 21.80±0.11 | 21.74±0.11 | C2PU-O | x |
| 2025-02-05T09:10:24 | 60711.382 | 7.184 | 10345.261 | <i>i'</i> | 22.45±0.20 | 22.39±0.20 | Euler | x |
| 2025-02-08T08:33:00 | 60714.356 | 10.158 | 14627.866 | <i>i'</i> | >22.25± | >22.19± | Euler | x |
| <i>I</i> band | | | | | | | | |
| 2025-01-29T05:15:46 | 60704.219 | 0.021 | 30.628 | <i>I</i> | 16.69±0.07 | 16.64±0.07 | Skynet | x |
| 2025-01-29T05:22:34 | 60704.224 | 0.026 | 37.424 | <i>I</i> | 16.56±0.05 | 16.51±0.05 | Skynet | x |
| 2025-01-29T05:30:34 | 60704.230 | 0.032 | 45.431 | <i>I</i> | 16.63±0.05 | 16.58±0.05 | Skynet | x |
| 2025-01-29T05:39:17 | 60704.236 | 0.038 | 54.143 | <i>I</i> | 16.74±0.05 | 16.69±0.05 | Skynet | x |
| 2025-01-29T05:49:29 | 60704.243 | 0.045 | 64.338 | <i>I</i> | 16.70±0.04 | 16.65±0.04 | Skynet | x |
| 2025-01-29T06:01:24 | 60704.251 | 0.053 | 76.261 | <i>I</i> | 16.85±0.04 | 16.80±0.04 | Skynet | x |
| 2025-01-29T06:15:21 | 60704.261 | 0.063 | 90.215 | <i>I</i> | 16.98±0.04 | 16.93±0.04 | Skynet | x |
| 2025-01-29T06:36:20 | 60704.275 | 0.077 | 111.196 | <i>I</i> | 17.19±0.03 | 17.14±0.03 | Skynet | x |
| 2025-01-29T21:35:47 | 60704.900 | 0.702 | 1010.650 | <i>I</i> | 19.14±0.10 | 19.08±0.10 | KNC | x |
| 2025-01-30T01:19:13 | 60705.055 | 0.857 | 1234.067 | <i>I</i> | 18.97±0.11 | 18.91±0.11 | KNC | x |
| 2025-02-02T19:02:22 | 60708.793 | 4.595 | 6617.230 | <i>I</i> | >20.69± | >20.64± | Generic | x |
| <i>z</i> band | | | | | | | | |
| 2025-02-04T02:59:50 | 60710.125 | 5.927 | 8534.685 | <i>z'</i> | 20.97±0.20 | 20.93±0.20 | C2PU-O | x |
| 2025-02-04T05:42:14 | 60710.238 | 6.040 | 8697.085 | <i>z'</i> | 21.81±0.16 | 21.77±0.16 | Artemis | x |
| 2025-02-05T05:41:13 | 60711.237 | 7.039 | 10136.076 | <i>z'</i> | 22.20±0.20 | 22.16±0.20 | Artemis | x |

Appendix E: Computation of the energy injection in NMMA

Energy Injection We introduce an energy injection parameter $\Delta \log_{10} E_0$ that starting from time t_{inj} linearly increases the log jet energy within the interval in NMMA and AFERTGLOWPY. Δt_{inj} from $\log_{10} E_0$ to $\log_{10} E_0 + \Delta \log_{10} E_0$ at time $t_{\text{inj}} + \Delta t_{\text{inj}}$, i.e.,

$$\log_{10} E_{k,\text{iso}}(t) = \begin{cases} \log_{10} E_{k,\text{iso}} & t < t_{\text{inj}} \\ \log_{10} E_{k,\text{iso}} + \Delta \log_{10} E \frac{t-t_{\text{inj}}}{\Delta t_{\text{inj}}} & t_{\text{inj}} < t < t_{\text{inj}} + \Delta t_{\text{inj}} \\ \log_{10} E_{k,\text{iso}} + \Delta \log_{10} E & t > t_{\text{inj}} + \Delta t_{\text{inj}}, \end{cases} \quad (\text{E.1})$$

Likelihood function definition To infer the posterior $p(\vec{\theta}|d)$ from the light curve data d , we sample the parameter space of the model using the nested sampling algorithm as implemented in PYMULTINEST (Feroz et al. 2009; Buchner et al. 2014). In particular, we use the likelihood function $\ln \mathcal{L}(\vec{\theta}|d)$ (see Appendix E for further details on its computation)

$$\ln \mathcal{L}(\vec{\theta}|d) = \sum_{t_j} \left(-\frac{1}{2} \frac{(m(t_j) - m^*(t_j, \vec{\theta}))^2}{\sigma(t_j)^2 + \sigma_{\text{sys}}^2} + \ln(2\pi(\sigma(t_j)^2 + \sigma_{\text{sys}}^2)) \right). \quad (\text{E.2})$$

This likelihood function compares the observed magnitudes $m(t_j)$ at times t_j to the model predictions $m^*(t_j, \vec{\theta})$ from AFERTGLOWPY. Here, $\sigma(t_j)$ represents the measurement uncertainties, and σ_{sys} denotes the systematic uncertainty.

Average chi-squared statistic Using posterior light curves derived from the ‘‘early time’’ data, we compute the average chi-squared statistic, $\langle \chi_j^2 \rangle$, for each data point d_j :

$$\langle \chi_j^2 \rangle = \int \left[\frac{(m(t_j) - m^*(t_j, \vec{\theta}))^2}{\sigma(t_j)^2 + \sigma_{\text{sys}}^2} \right] p(\vec{\theta}|d) d\vec{\theta}, \quad (\text{E.3})$$