

Evidence of Energy Injection in the Short and Distant GRB 250221A

Camila Angulo-Valdez ^{1,*}, Rosa L. Becerra ^{2,†}, Ramandeep Gill ³, Noémie Globus ⁴, William H. Lee ¹,
Diego López-Cámara ⁶, Cassidy Mihalenko ^{5,17}, Enrique Moreno Méndez ⁷, Roberto Ricci ²,
Karelle Siellez ⁵, Alan M. Watson ¹, Muskan Yadav ², Yu-Han Yang ², Dalya Akl ^{11,19}, Sarah Antier ¹⁸,
Jean-Luc Atteia ¹³, Stéphane Basa ^{8,9}, Nathaniel R. Butler ¹⁴, Simone Dichiarà ¹⁵, Damien Dornic ¹²,
Jean-Grégoire Ducoin ¹², Francis Fortin ¹³, Leonardo García-García ⁴, Kin Ocelotl López ¹,
Francesco Magnani ¹², Brendan O'Connor ¹⁶, Margarita Pereyra ^{4,20}, Ny Avo Rakotondrainibe ⁸,
Fredd Sánchez-Álvarez ¹, Benjamin Schneider ⁸, Eleonora Troja ², Antonio de Ugarte Postigo ⁸

¹ Universidad Nacional Autónoma de México. Instituto de Astronomía. A.P. 70-264, 04510. Ciudad de México, México.

² Department of Physics, University of Rome - Tor Vergata, via della Ricerca Scientifica 1, 00100 Rome, IT

³ Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro # 8701, Ex-Hda. San José de la Huerta, Morelia, Michoacán, México C.P. 58089, México

⁴ Instituto de Astronomía, Universidad Nacional Autónoma de México, km 107 Carretera Tijuana-Ensenada, 22860 Ensenada, Baja California, México

⁵ School of Natural Sciences, Private Bag 37, University of Tasmania, Hobart, 7001 TAS, Australia

⁶ Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-264, 04510 México, CDMX, Mexico

⁷ Facultad de Ciencias, Universidad Nacional Autónoma de México, Apartado Postal 70-264, 04510 México, CDMX, Mexico

⁸ LAM, Université Aix-Marseille & CNRS, UMR7326, 38 rue F. Joliot-Curie, 13388 Marseille Cedex 13, France

⁹ Aix-Marseille University, CNRS, OSU-Pythéas, France

¹⁰ Observatoire de la Côte d'Azur, ARTEMIS, Nice, France

¹¹ New York University Abu Dhabi, PO Box 129188, Saadiyat Island, Abu Dhabi, UAE

¹² Aix Marseille University, CNRS, CPPM, Marseille, France

¹³ IRAP, Université de Toulouse, CNRS, CNES, UPS, 31401 Toulouse, France

¹⁴ School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA

¹⁵ Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA

¹⁶ McWilliams Center for Cosmology and Astrophysics, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA

¹⁷ ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), John St, Hawthorn, VIC 3122, Australia

¹⁸ IJCLAB, Université Paris Saclay, Orsay, France

¹⁹ Center for Astrophysics and Space Science (CASS), New York University Abu Dhabi, Saadiyat Island, PO Box 129188, Abu Dhabi, UAE

²⁰ Secretaría de Ciencia, Humanidades, Tecnología, e Innovación

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We present the photometric and spectroscopic analysis of the short-duration GRB 250221A ($T_{90} = 1.80 \pm 0.32$ s), using a data set from the optical facilities COLIBRÍ, the Harlingen 50 cm Telescope, and the Very Large Telescope. We complement these observations with data from the *Neil Gehrels Swift Observatory* and the *Einstein Probe*, as well as radio observations from the Very Large Array. GRB 250221A is among the few short GRBs with direct afterglow spectroscopy, which gives a secure redshift determination of $z = 0.768$ and allows the unambiguous identification of the host as a galaxy with a star-formation rate of $\sim 3 M_{\odot} \text{ yr}^{-1}$. The X-ray and optical light curves up to $T_0 + 10$ ks (where T_0 refers to the GRB trigger time) are well described by forward-shock synchrotron emission in the slow-cooling regime within the standard fireball framework. However, at $T_0 + 0.6$ days, both the X-ray and optical bands exhibit an excess over the same interval, which we interpret as evidence of energy injection into a jet with a half-opening angle of $\theta_j = 11.5^\circ$ through a refreshed shock powered by late central engine activity or a radially stratified ejecta. The burst properties (duration, spectral hardness, peak energy, and location in the Amati plane) all favour a compact binary merger origin. However, our modelling of the afterglow suggests a dense circumburst medium ($n \sim 80 \text{ cm}^{-3}$), which is more typical of a Collapsar environment. This tension over the classification of this burst (short-hard vs. long-soft) as inferred from the prompt and afterglow emissions makes GRB 250221A an unusual event and underscores the limitations of duration-based classifications and the importance of multi-wavelength, time-resolved follow-up observations.

Key words: (stars:) gamma-ray burst: individual: GRB 250221A – (transients:) gamma-ray bursts

* E-mail: camiangulo@astro.unam.mx (CAV)

† E-mail: rosa.becerra@roma2.infn.it (RLB)

1 INTRODUCTION

Gamma-ray bursts (GRBs) are the most luminous electromagnetic phenomena observed in the universe (Atteia et al. 2017) and are powered by ultra-relativistic jets, with an overall duration dichotomy that is usually associated to two different types of progenitors (Kouveliotou et al. 1993). Short GRBs (SGRBs) have durations $T_{90}^1 \lesssim 2$ seconds and a relatively hard spectrum, characterized through the hardness ratio (HR²), and are believed to result from the merger of compact binary systems with at least one neutron star (NS) involved (see, e.g., Paczynski 1986; Paczyński 1991; Lee & Ramirez-Ruiz 2007; Berger 2014; Abbott et al. 2017). On the other hand, long GRBs (LGRBs) are thought to be the result of the core-collapse of a Wolf-Rayet star (with a stripped H and He envelope) whose mass exceeds about $10M_{\odot}$ and are associated with type Ic supernovae (SNe) (see, e.g., Woosley 1993; MacFadyen & Woosley 1999a; Hjorth & Bloom 2012).

However, this duration-based classification has important limitations, which can be seen in several cases, including: hybrid events such as the long GRB 211211A ($T_{90} = 51.37 \pm 0.80$ s) (Troja et al. 2022; Yang et al. 2022; Rastinejad et al. 2022) and GRB 230307A ($T_{90} \sim 35$ s) (Yang et al. 2024; Levan et al. 2024), but with an identified kilonovae (KNe) signature; the short-duration GRB 200826A ($T_{90} = 1.4 \pm 0.13$ s) linked to the collapse of a massive star (Ahumada et al. 2021); and unusual events such as GRB 210704A possibly produced by the coalescence between a neutron star and a white dwarf (Becerra et al. 2023). This motivates the use of additional diagnostics, in particular the properties of the afterglow and host environment, to distinguish between progenitors.

Supernovae and kilonovae are the smoking gun signatures of the progenitors. However, they are not detectable at high redshift. In such cases, the afterglow and burst environment become the primary diagnostics. In this context, the multi-frequency afterglow is a powerful probe. While the fireball model (Goodman 1986; Paczynski 1986; Shemi & Piran 1990; Rees & Meszaros 1992; Meszaros & Rees 1993), captures the overall prompt and afterglow evolution (see Kumar & Zhang 2015, for a review), many optical light curves show deviations such as flares, plateaus, and rebrightening episodes (Sari & Mészáros 2000; Lazzati et al. 2002; Petropoulou et al. 2020; Dainotti et al. 2024; Gendre 2025). The physical origin of these features remains debated, with possible explanations including late-time central engine activity (Li et al. 2012), energy injection (Laskar et al. 2015), refreshed shocks (Vlasis et al. 2011; Lamb et al. 2019), or interaction with a structured circumburst medium (CBM). Such signatures are particularly relevant when the progenitor classification is uncertain, since they may reveal information about both the central engine and the environment.

Complementary to the photometric information, spectroscopy is essential for a complete understanding of every event. It provides the only direct means of determining redshift, offers clues about the host galaxy and the environment of the burst, and helps constrain the progenitor system.

Optical spectroscopy of SGRB host galaxies is particularly challenging because these systems are typically faint and associated with older stellar populations (O'Connor et al. 2022; Fong et al. 2022; Nugent et al. 2022). Nonetheless, when successful, such observations

yield valuable information on the global environment in which these transients occur.

Even more powerful, however, is the spectroscopy of the afterglow itself. Unlike host observations, which probe the large-scale properties of the galaxy, afterglow spectroscopy provides a direct snapshot of the line of sight at the moment of the explosion. Optical and near-infrared spectra can reveal absorption features from the host interstellar medium, such as Mg II, Fe II, and Ca II, and occasionally fine-structure lines excited by the intense GRB radiation (Prochaska et al. 2007; Vreeswijk et al. 2013; Selsing et al. 2018). Such measurements are exceedingly rare, as SGRB afterglows are typically fainter and fade much faster than those of LGRBs, but successful detections deliver uniquely detailed information about the immediate environment of the burst (de Ugarte Postigo et al. 2014; O'Connor et al. 2022; Agüí Fernández et al. 2023).

In this paper, we present an analysis of both the early- and late-time observations of the multi-frequency afterglow of GRB 250221A. This is one of the few SGRB afterglows (only the fourth case in the sample of over 150 SGRBs discovered by *Swift*) with clear absorption lines in its spectrum, allowing us to securely measure its redshift $z \approx 0.768$ and break the degeneracy with a nearby, unrelated galaxy at $z \approx 0.343$. Its late-time afterglow shows an unusual rebrightening starting at ~ 0.6 d post-burst — later and more pronounced than in most previously reported events (see, e.g., Troja et al. 2007; Becerra et al. 2019a,b; Pereyra et al. 2022; Nardini et al. 2011; Kobayashi & Zhang 2003; Li et al. 2012; Kann et al. 2010) — making it an outstanding event for investigating how such features connect to progenitor type and environment. By combining early- and late-time multi-wavelength photometry with spectroscopy of the host candidates, this burst allows us to explore the mechanisms behind rebrightening and assess their implications for GRB classification. We examine its high-energy characteristics during the prompt phase, including duration, isotropic energy, and spectral peak energy, along with multi-wavelength observations of the afterglow in the X-ray, optical, and radio bands extending up to 10 days post-burst.

The paper is organised as follows. In Section 2, we describe the photometric and spectroscopic data sets, including observations in gamma-rays from *Swift*/BAT, X-rays from *Swift*/XRT and *Einstein Probe*, optical data from COLIBRI, the Harlingen 50-cm Telescope, and the Very Large Telescope (VLT), and radio observations from the Very Large Array (VLA). In Section 3 we analyse the environment of GRB 250221A and discuss the properties of the potential host galaxy candidates. In Section 4, we present the physical interpretation of our data, including the light curve and spectral evolution of GRB 250221A. We discuss our findings in Section 5 and summarise our conclusions in Section 6.

Throughout this work, we adopt a flat Λ CDM cosmology with BAO with $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.31$ (Planck Collaboration et al. 2020).

2 OBSERVATIONS

2.1 High-Energies

The *Swift*/Burst Alert Telescope (BAT) instrument on the *Neil Gehrels Swift Observatory* triggered on GRB 250221A $T_0 = 2025$ February 21 03:34:37 UTC (Caputo et al. 2025). Simultaneously, Konus-Wind also triggered the source (Frederiks et al. 2025). The burst consists of a single short pulse with $T_{90} = 1.8 \pm 0.3$ s in the 15–350 keV band, best fit by a power-law spectrum with photon index 1.43 ± 0.23 (Palmer et al. 2025). According to this best fit model, the

¹ The duration over which the central 90% of the photons from the GRB are detected.

² The energy or fluence contained within one band compared to another, where SGRBs usually emit more high-energy radiation than LGRBs.

fluence in the 15–150 keV band is $(3.9 \pm 0.6) \times 10^{-7}$ erg cm $^{-2}$ and the 1-s peak flux is 2.9 ± 0.5 ph cm $^{-2}$ s $^{-1}$.

At the time of the *Swift*/BAT trigger, all three LIGO–Virgo detectors were operating nominally with ranges of 157, 162, and 52 Mpc. The closest GW candidate (S250221ap, 126 s later) was at 811 ± 250 Mpc with a high FAR, making it incompatible with GRB 250221A.

The *Swift*/X-ray Telescope (XRT) began observations 79 s after the trigger, detecting a fading X-ray counterpart at RA, Dec (J2000) = 03:57:51.03, $-15:08:01.3$ with an error radius of $1.9''$ at the 90% confidence level (c. l.; Caputo et al. 2025). XRT light curves and spectra were obtained from the public online repository (Evans et al. 2009) hosted by the UK Swift Science Data Centre³.

The X-ray afterglow is observed to decay as a simple power-law with slope 0.97 ± 0.04 (0.3–10 keV), falling below the XRT sensitivity within 1 day. Subsequent monitoring was carried out with the Fast X-ray Telescope (FXT) aboard *Einstein Probe*.

Two FXT follow-up observations (PI: Troja) were conducted at $T_0 + 2.07$ d and $T_0 + 5.68$ d with total exposures of 5 ks and 4 ks, respectively. Data were acquired in Full Frame mode with the Thin Filter, and processed using the FXT Data Analysis Software (FXTDAS v.1.10). Aperture photometry of the source was performed using a circular region with a $40''$ radius to estimate the source counts and a concentric annular region with radii of $60''$ and $180''$ to estimate the background. The unabsorbed flux is $(2.3^{+0.3}_{-0.2}) \times 10^{-13}$ erg cm $^{-2}$ and $(2.4^{+1.4}_{-1.0}) \times 10^{-14}$ erg cm $^{-2}$ in the 0.3–10 keV range, respectively (see Table 1).

2.2 Optical

2.2.1 COLIBRÍ

We observed the afterglow of GRB 250221A with the DDRAGO wide-field imager on the COLIBRÍ telescope. COLIBRÍ⁴ is a Franco-Mexican fast, robotic 1.3 m telescope operated by the Observatorio Astronómico Nacional (OAN) in the Sierra de San Pedro Mártir, Baja California (Basa et al. 2022). DDRAGO is a two-channel imager with the blue channel working in *gri* and the red in *zy* (Langarica et al. 2024). 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 $15 \mu\text{m}$ pixels. The scale is $0.38''/\text{pixel}$ and the field is $25.9'$ square. During our observations, the red channel was not available.

Our observations of GRB 250221A used the *g*, *r*, and *i* filters, which closely match the SDSS/Pan-STARRS filter system. The color-term coefficients for *g* – *r* for transforming to Pan-STARRS DR1 magnitudes are -0.05 , $+0.00$, and -0.04 for *g*, *r*, and *i*, respectively.

The COLIBRÍ control system received an initial *Swift*/BAT notification of the burst via the GCN system at 2025 February 21 03:35:03 UTC ($T_0 + 26$ seconds). The telescope immediately interrupted its ongoing observations and slewed to the burst location. The first exposure began at 03:35:56 UTC ($T_0 + 79$ seconds) at an airmass of about 1.7. All exposures were 60 seconds, with a dead time of about 20 seconds between each exposure for read-out and dithering. The final exposure of the first night occurred at 05:11:31 UTC (1.62 hours after the trigger), by which time the airmass had increased to 2.81 and the transparency had decreased noticeably.

The initial exposures were in the *i* filter (chosen as the reddest

filter available, to minimize the possibility of drop-out in *g* and *r* for higher-redshift GRBs). The 60-second exposures taken between $T_0 + 0.30$ and $T_0 + 1.34$ hours were combined in groups of 5 to increase the signal-to-noise ratio. Towards the end of the first night, starting at $T_0 + 1.06$ hours, we obtained a sequence of 24 exposures alternating between the *g*, *r*, and *i* filters. In the following nights, all the observations were only carried out in the *r* filter.

We reduced and coadded the images using custom software to carry out sky subtraction, image alignment, and coaddition. Our photometry is included in Table 1 and is plotted in Figure 1.

We identified a bright, uncatalogued source at RA, Dec (J2000) = 03:57:51.07, $-15:07:59.52$, with an uncertainty of $0.5''$, consistent with the *Swift*/UVOT position (Caputo et al. 2025), and reported this in Watson et al. (2025).

2.2.2 Harlinton 50-cm Telescope

We also observed the afterglow of GRB 250221A with the Harlinton 50-cm Telescope of the University of Tasmania Greenhill Observatory. The telescope is equipped with an Apogee Alta U42 CCD with 2048×2048 pixels each of $13 \mu\text{m}$, giving a field of 27.2 arcmin and a pixel scale of $0.8''/\text{pixel}$, and an Apogee FW50-10S filter wheel with Bessell *B* and *V*, SDSS *g'*, *r'*, and *i'*, and narrowband filters.

We obtained multiple 60-second exposures in the *r'* filter. We reduced and coadded the images using custom software to carry out sky subtraction, image alignment, and co-addition. Our final stack contains 960 s of exposure.

2.2.3 Very Large Telescope

We observed the field of GRB 250221A with the X-shooter spectrograph on ESO’s VLT UT3 (Melipal; 114.27LW.022; PI: Troja). Observations began at $T_0 + 21.4$ hours and were carried out at an average airmass of 1.2 for a total exposure of 4×600 s with seeing of approximately $1.0''$.

We used a $1''$ and $0.9''$ slit widths in the UVB and VIS/NIR arms respectively, shown by the rectangle in the first panel of Figure 2, and a nodding ABAB observing scheme with a nodding throw of $5''$ to minimize the background in the near-infrared (NIR) arm. Exposures from each arm were reduced independently with custom software based on the official ESO pipeline⁵ (Modigliani et al. 2010). The pipeline performs bias subtraction, flat correction, bad-pixel masking, order tracing and rectification, wavelength calibration, and sky subtraction, followed by flux calibration using the instrument response and standard-star catalogue when available.

Imaging observations were carried out with the FORS2 instrument on UT1 (Antu) in three epochs (see Table 1; PI: Troja). For the first epoch, we observed the target with the *R_SPECIAL*, *I_BESS*, and *z_GUNN* filters. Observations began at 00:42:31 UTC on 2025 February 22 ($T + 0.89$ days) with an average seeing of $\sim 1.3''$.

The second epoch of observations was conducted on 2025 February 26 ($T_0 + 4.88$ days), starting at 00:30:46 UTC. Images were obtained in the *R* and *I* filters, with total exposure times of 1440 s and 1920 s, respectively. A third epoch was obtained at $T_0 + 11.86$ days, also in the *R* and *I* filters, to facilitate image subtraction and to characterize the host galaxy of GRB 250221A (see Table 1).

Images were processed following standard techniques for CCD

³ <https://www.swift.ac.uk/>

⁴ <https://www.colibri-obs.org/>

⁵ https://www.eso.org/sci/software/pipe_aem_main.html

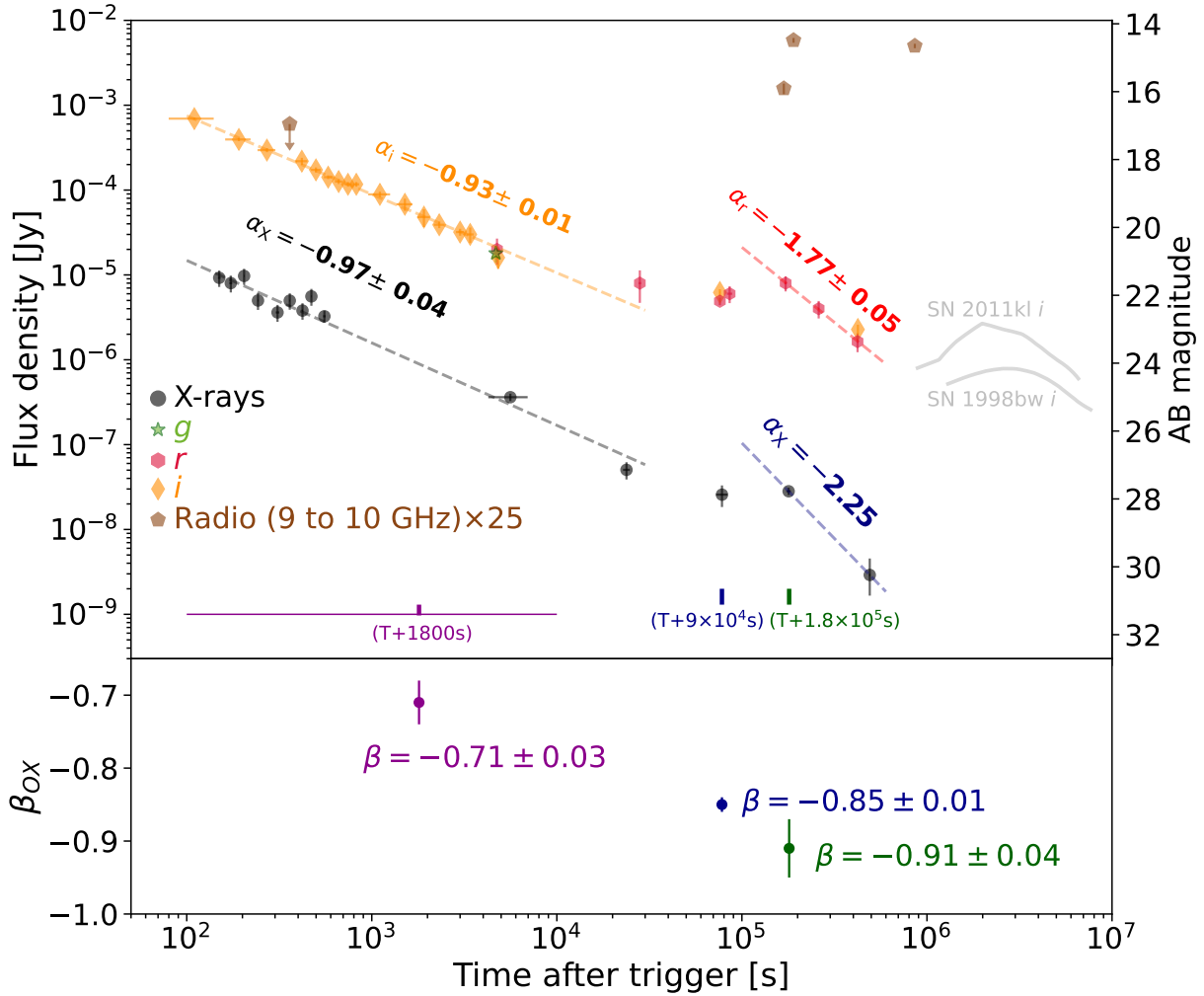


Figure 1. *Top:* X-ray (0.3–10.0 keV, at 1 keV, black circles), optical (yellow diamonds for *i*, red hexagons for *r*, green stars for *g*) and radio (at 9 GHz from ATCA (Gulati et al. 2025) and 10 GHz from VLA, brown pentagons) observations of GRB 250221A. The dashed lines show the power-law fits to the afterglow for X-rays (fitted before $T \lesssim 2 \times 10^4$ s and after $T > 10^5$ s) and optical (fitted for $T < 10^4$ s for the *i* band and at $T > 10^5$ s for the late *r* band). *Bottom:* Optical-to-X-rays spectral indices for three different epochs, the first from $T_0 + 100$ s to $T_0 + 10^4$ s, with a median arrival time of the X-rays photons at $T_0 + 1800$ s (see Figure 7) (purple), second at $T_0 + 9 \times 10^4$ s (blue), and third at $T_0 + 1.8 \times 10^5$ s (green). We also illustrate the optical light curves of SN1998bw (Galama et al. 1998; Clocchiatti et al. 2011) and SN2011kl (Greiner et al. 2015) (placed at $z = 0.768$) to highlight that the excess is similar in brightness (in the optical) but differs in timescale.

data reduction (e.g., bias subtraction, flat-fielding, cosmic-ray rejection), aligned using SCAMP and coadded with SWarp (Bertin 2006, 2010).

2.2.4 Other Optical and Infrared Observations

Optical observations of GRB 250221A were also performed by the Rapid Eye Mount (REM) 60 cm robotic telescope (Melandri et al. 2025), 0.36 m telescope in the Al-Khatim Observatory (Odeh et al. 2025), 1.6 m Multi-channel Photometric Survey Telescope (Mephisto) (Guo et al. 2025), the Nordic Optical Telescope (NOT) (Cotter et al. 2025), GRANDMA/TAROT (Muentner et al. 2025), the AZT-20 telescope at the Assy-Turgen Observatory (Pankov et al.

2025a), the AZT-33IK telescope at the Mondy Observatory (Pankov et al. 2025b), the 1-meter Sinistro telescope at the Las Cumbres Observatory Global Telescope (LCOGT) (Ghosh et al. 2025), the 80 cm Tsinghua-Nanshan Optical Telescope (TNOT) (Iskandar et al. 2025). GRB 250221A was also detected in the near IR, in the *H* filter, by REM (Melandri et al. 2025).

2.3 Radio

We observed the field of GRB 250221A with the Karl G. Jansky Very Large Array (VLA) at a central frequency of 10 GHz (X-band), using a total bandwidth of 4 GHz. The first epoch was obtained at a mid-time of $T_0 + 1.95$ days post-trigger. At the time of this observation,

Table 1. Optical and radio photometry of GRB 250221A from this work. Optical values are corrected by Galactic extinction.

X-rays						
Telescope	Instrument	Mid Time [hrs]	Energy Range		Exposure Time [ks]	Flux [erg cm ⁻²]
EP	FXT	49.68	0.3–10	...	5	$(2.28^{+0.28}_{-0.24}) \times 10^{-13}$
EP	FXT	136.32	0.3–10	...	4	$(2.36^{+1.35}_{-1.02}) \times 10^{-14}$
Optical						
Telescope	Instrument	Mid Time [hrs]	Filter	AB Magnitude	Exposure Time [s]	Flux [μ Jy]
COLIBRÍ	DDRAGO	0.03	i	16.80 ± 0.04	60	634.08 ± 21.35
COLIBRÍ	DDRAGO	0.05	i	17.41 ± 0.05	60	360.36 ± 18.00
COLIBRÍ	DDRAGO	0.08	i	17.72 ± 0.07	60	270.02 ± 16.68
COLIBRÍ	DDRAGO	0.12	i	18.04 ± 0.11	60	200.36 ± 20.93
COLIBRÍ	DDRAGO	0.14	i	18.30 ± 0.08	60	158.09 ± 11.95
COLIBRÍ	DDRAGO	0.16	i	18.52 ± 0.06	60	129.36 ± 7.12
COLIBRÍ	DDRAGO	0.18	i	18.65 ± 0.08	60	114.73 ± 8.11
COLIBRÍ	DDRAGO	0.21	i	18.73 ± 0.08	60	106.87 ± 7.56
COLIBRÍ	DDRAGO	0.23	i	18.73 ± 0.08	60	106.59 ± 7.49
COLIBRÍ	DDRAGO	0.31	i	19.02 ± 0.09	300	17.89 ± 6.81
COLIBRÍ	DDRAGO	0.42	i	19.32 ± 0.19	300	81.54 ± 6.78
COLIBRÍ	DDRAGO	0.53	i	19.70 ± 0.28	300	62.17 ± 11.08
COLIBRÍ	DDRAGO	0.64	i	19.92 ± 0.10	300	43.60 ± 11.29
COLIBRÍ	DDRAGO	0.83	i	20.12 ± 0.11	300	35.63 ± 3.40
COLIBRÍ	DDRAGO	0.94	i	20.22 ± 0.25	300	29.57 ± 2.97
COLIBRÍ	DDRAGO	1.29	g	20.69 ± 0.25	300	27.15 ± 6.19
COLIBRÍ	DDRAGO	1.32	r	20.64 ± 0.41	300	16.00 ± 4.00
COLIBRÍ	DDRAGO	1.34	i	20.90 ± 0.31	300	14.50 ± 4.20
50cm	Harlingten	7.80	r	21.67 ± 0.52	960	6.92 ± 3.31
VLT	FORS2	21.12	i	21.91 ± 0.10	720	4.37 ± 0.49
VLT	FORS2	21.12	r	22.17 ± 0.06	720	5.70 ± 0.57
COLIBRÍ	DDRAGO	23.85	r	21.94 ± 0.27	5640	5.46 ± 1.35
COLIBRÍ	DDRAGO	47.85	r	21.63 ± 0.24	5160	7.15 ± 1.61
COLIBRÍ	DDRAGO	72.21	r	22.28 ± 0.25	4020	3.96 ± 0.93
VLT	FORS2	117.12	r	23.36 ± 0.07	1440	1.46 ± 0.41
VLT	FORS2	117.60	i	23.00 ± 0.15	720	2.08 ± 0.31
Radio						
Telescope	Instrument	Mid Time [hrs]	Band		Exposure Time [s]	Flux [μ Jy]
VLA	...	46.80	X (10 GHz)	...	900	63.00 ± 9.00
VLA	...	238.80	X (10 GHz)	...	900	200.00 ± 12.00

the array was transitioning from configuration A to D. To account for this, the longer baselines were excluded from the visibilities, resulting in an angular resolution of 7.3". The total integration time on source was 15 minutes. Data were flagged and calibrated using the VLA online CASA pipeline v6.6.1 (CASA Team et al. 2022), and imaged and cleaned using the TCLEAN task (CASA Team et al. 2022) with a Briggs weighting factor of 0.5. We detected a weak source at the target position with a flux density of $63 \pm 9 \mu\text{Jy}$ (Ricci & Troja 2025). Given the early epoch of these observations, the measurement may be affected by interstellar scintillation (ISS).

As part of our radio campaign, we performed a second observation with the VLA on 2025 March 3 (at a mid-time of $T_0 + 9.95$ days) with the same frequency set-up. The array configuration was D resulting in an angular resolution of 7.2". The total integration time on the source was 15 minutes. The source flux density increased to $(200 \pm 12) \mu\text{Jy}$, similar to the ATCA value reported eight days before (Gulati et al. 2025). For our VLA campaign, the root mean square *rms* noise in the cleaned radio map and flux density statistical uncertainty were determined using the IMSTAT task (CASA Team et al. 2022) in a region of the map far from bright radio emission.

Figure 1 includes the radio photometry described above. In this plot, we notice a significant difference between our measurements at $T_0 + 2.0$ d and the fluxes reported by Gulati et al. (2025) at $T_0 + 2.4$ days. Such large fluctuations are not uncommon in radio afterglows of highly relativistic sources such as GRBs and FXTs (Yadav et al. 2025).

2.4 Data Analysis and Photometry

The afterglow of GRB 250221A is projected close to two galaxies (see Section 3.1). Therefore, we performed image subtraction using the Saccadic Fast Fourier Transform (SFFT) (Hu et al. 2022) software using as templates the third epoch of observations with FORS2 for *r* and archival images from Pan-STARRS DR1 (Magnier et al. 2020) for *g* and *i*.

The PSF photometry was performed using a custom pipeline and the calibration including SExtractor (Bertin & Arnouts 1996). To minimize systematic errors in the calibration, we calibrated all our photometry using the Pan-STARRS PS1 DR2 Catalog (Magnier et al. 2020).

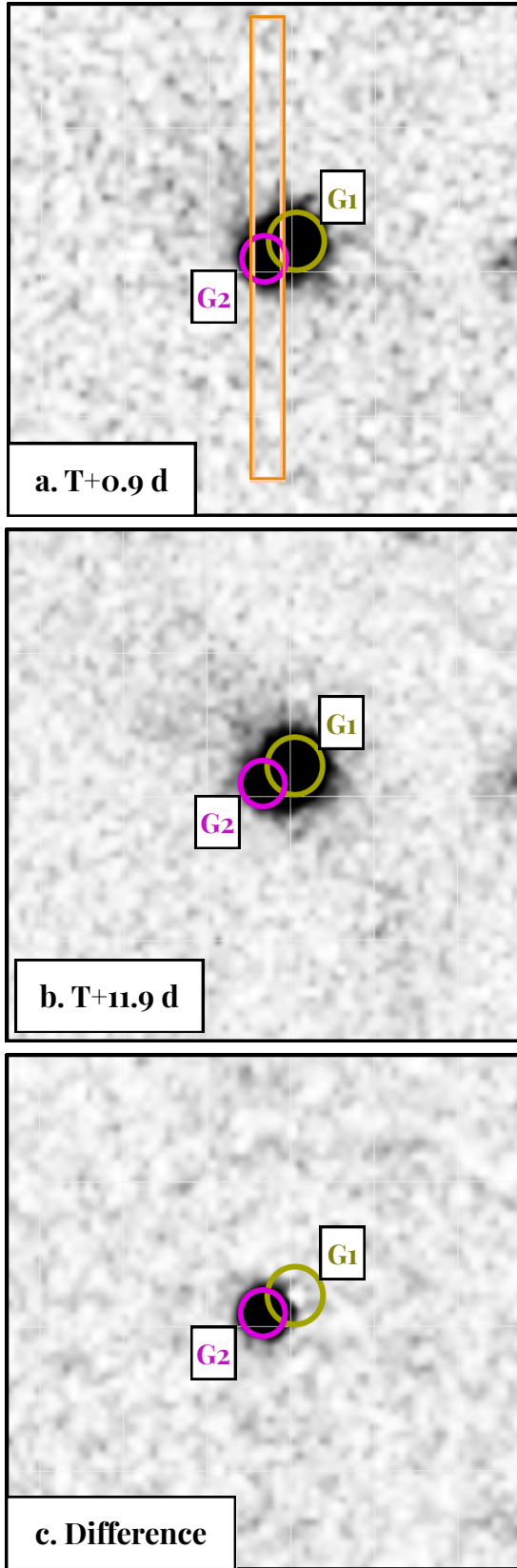


Figure 2. Field of GRB 250221A. We show the R filter image obtained with the VLT/FORS2 after $T_0 + 0.9$ days (panel a) and $T_0 + 11.9$ days (panel b). We also show the contribution of the afterglow after image subtraction (panel c). We highlight the presence of two galaxies at $photo - z = 0.343 \pm 0.077$ (G1, green circle; according to the Legacy Survey DR10 [Dey et al. 2019](#)) and at $z = 0.768$ (G2, magenta circle).

Our magnitudes are in the natural AB system without the application of any colour terms and are corrected for the Galactic extinction in the direction of the burst $E_{(B-V)} = 0.0473 \pm 0.0015$ ([Schlegel et al. 1998](#)), which implies extinctions of $A_g = 0.18$, $A_r = 0.13$, and $A_i = 0.09$.

The detailed photometry from COLIBRÍ, Harlingen 50-cm, and VLT is listed in Table 1 and shown in Figure 1.

3 HOST GALAXY

3.1 Environment

Figure 2 shows the field of GRB 250221A from the VLT observations in R filter at $T_0 + 0.9$ and $T_0 + 11.9$ days, along with the corresponding difference image highlighting the afterglow emission.

A bright galaxy is located about $1.15''$ to the NW of the optical afterglow. This object is shown with a green circle and will be referred to from now on as G1. According to the Legacy Survey DR10 ([Dey et al. 2019](#)), its AB magnitudes are $g = 22.17 \pm 0.02$, $r = 20.86 \pm 0.01$, $i = 20.34 \pm 0.01$, and $z = 20.05 \pm 0.01$. At the afterglow position, another fainter galaxy is visible with AB magnitudes of $g = 24.02 \pm 0.06$, $r = 24.09 \pm 0.08$, $i = 23.86 \pm 0.09$, and $z = 24.21 \pm 0.26$ ([Dey et al. 2019](#)). This object is shown with a magenta circle and will be referred to from now on as G2. The properties of both objects are summarized in Table 2.

Following [Bloom et al. \(2002\)](#) and the galaxy density estimation from deep optical imaging ([Metcalf et al. 2001](#); [Kashikawa et al. 2004](#); [McCracken et al. 2003](#)), the probability of finding an unrelated galaxy of magnitude m_r or brighter within the vicinity of a GRB can be approximated as:

$$P_{\text{ch}} = 1 - \exp\left(-\pi r_i^2 \times 10^{a(m_r - m_0) + b}\right), \quad (1)$$

with $a = 0.36$, $b = -2.42$, and $m_0 = 24$ for galaxies fainter than $m_r \gtrsim 19$ mag and $a = 0.56$, $b = -4.80$ and $m_0 = 18$ for brighter galaxies.

The effective radius r_i depends on the projected angular separation R_0 between the GRB and the galaxy and on the half-light radius R_{half} of the galaxy. We take $r_i = 2R_{\text{half}}$ for G2 since GRB 250221A is localized inside the detected light, whereas for G1 we use $r_i = (R_0^2 + 4R_{\text{half}}^2)^{1/2}$ because the GRB position is outside its detected light.

Using the photometric magnitudes from the Legacy Survey DR10 ([Dey et al. 2019](#)), $r = 20.86$ for G1 and $r = 24.09$ for G2, we estimate chance coincidence probabilities of $P_{\text{ch}} = 0.009$ and $P_{\text{ch}} = 0.003$, respectively (see Table 2), which makes both candidates equivalent possible host galaxies of GRB 250221A. Therefore, using only standard positional arguments, the host galaxy and distance of GRB 250221A would remain uncertain.

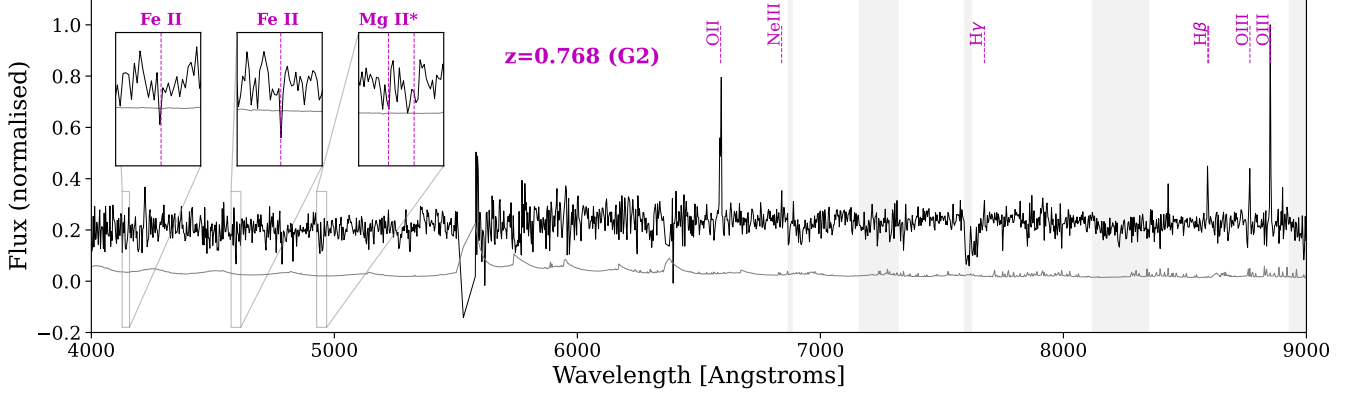
3.2 Determination of the redshift and identification of the host galaxy

We determined the redshift by continuum-subtracting the spectra, detecting significant emission and absorption features, and cross-matching them with a set of expected rest-frame lines (Fe II, Mg II, O II, O III, Ne II, Ne III, and Balmer transitions). Candidate redshifts were refined by minimizing residuals between observed and predicted wavelengths, and confirmed through consistency across multiple lines.

In the combined spectrum, shown in Figure 3, we detect strong evidence of the presence of emission lines of O III (5007 Å), O III

Table 2. Properties of the host galaxy candidates of GRB 250221A.

Label	RA	DEC	z	m_r	$R_{\text{half}} [']$	$R_0 [']$	Offset δR [kpc]	d_L [Gpc]	d_A [Gpc]	$P_{\text{ch}} (< R_0)$
G1	59.4625	-15.1331	0.343	20.86 ± 0.01	0.77	1.15	11 ± 5	1.95	1.06	0.009
G2	59.4628	-15.1333	0.768	24.09 ± 0.08	0.42 ⁶	0.29	$< 7^{+12}_{-7}$	4.91	1.57	0.003

**Figure 3.** VLT/X-shooter optical spectrum of GRB 250221A (black line) and its corresponding 1σ error (gray line), obtained at $T_0 + 21.4$ hours. We identify emission lines of [O II], [Ne III], H γ , H β , and [O III] along with ISM absorption lines from Mg II, Fe II, all consistent with a redshift of $z = 0.768$ (magenta). We also zoom in on the H α emission line (which, for readability, is not shown in the main figure) using the same y-axis interval adopted for the estimation of the star formation rate of G2 (see Section 3.2). We also illustrate the telluric lines (gray shaded regions).

(4959 Å), H β (4861 Å), O II (3726/3729 Å), Ne III (3859 Å), and the absorption ISM signatures of the lines Mg II (2796/2803 Å) and Fe II (2344/2600 Å) at a common redshift of $z = 0.768$. Due to the presence of these features on the GRB afterglow, one can be certain that the burst lies behind the absorber — otherwise, the continuum would not be attenuated. Therefore, we can unambiguously identify G2 as the host galaxy of GRB 250221A. This result is consistent with the spectroscopic redshift reported by Palmerio et al. (2025). This result underscores the value of early-time afterglow spectroscopy, which allows an unequivocal identification of the host galaxy, something not always achievable statistically (see Section 3.1).

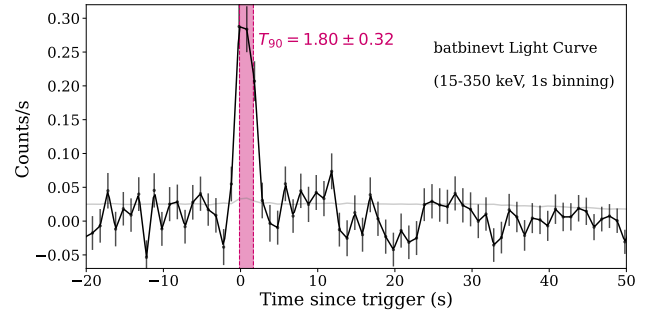
Moreover, the star-formation rate (SFR) of G2 was derived from the H α emission line in its rest-frame optical spectrum. Using the measured H α flux of $F(\text{H}\alpha) = (1.31 \pm 0.59) \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, we obtain an H α luminosity of $L(\text{H}\alpha) = 3.8 \times 10^{41} \text{ erg s}^{-1}$. The H β flux, $F(\text{H}\beta) = (4.67 \pm 1.00) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$, yields a Balmer decrement $\text{H}\alpha/\text{H}\beta = 2.81 \pm 1.40$, consistent with the case B recombination value of 2.86 and indicating negligible internal extinction (Osterbrock & Ferland 2006). Following the calibration of Kennicutt (1998, their Eq. 2), we derive an SFR of $\sim 3 M_{\odot} \text{ yr}^{-1}$ assuming a Salpeter initial mass function (Salpeter 1955). This value is consistent with those typically measured for GRB host galaxies at redshift $z < 1.6$ (see Fig. 11 in Savaglio et al. 2009).

4 DATA ANALYSIS AND INTERPRETATION

4.1 GRB Properties: Classification, Energy and Luminosity Estimations

4.1.1 Duration

We retrieved the data products from the *Swift* Burst Analyser (ObsID: 01290305000) and constructed the *Swift*/BAT light curve of

**Figure 4.** Masked-weighted *Swift*/BAT (15–350 keV) light curve of GRB 250221A with 1 s binning produced with the HEASoft/FTOOLS software (black solid line). The background count rate is shown in gray. The T_{90} duration of 1.80 ± 0.32 s is indicated by the shaded magenta region.

the prompt emission using the HEASoft/FTOOLS software package⁷ (Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014). The light curve was generated with the batbinevt routine, which creates a mask-weighted light curve from the *Swift*/BAT event data. The resulting light curve spans the 15–350 keV energy range with uniform 1 s time bins.

The *Swift*/BAT light curve (15–350 keV) displayed in Figure 4 shows a single peak structure, with a duration of $T_{90} = 1.80 \pm 0.32$ seconds. The fluence was estimated with a value of $(3.9 \pm 0.6) \times 10^{-7} \text{ erg cm}^{-2}$ in the 15–150 keV band (Palmer et al. 2025).

⁷ <http://ftools.gsfc.nasa.gov/>

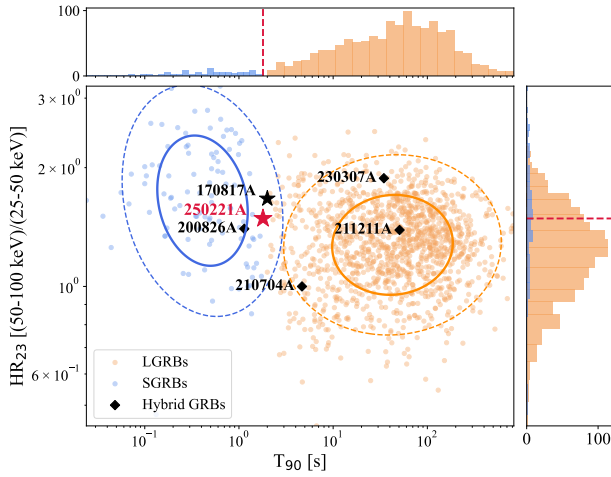


Figure 5. HR versus T_{90} diagram for GRB 250221A (crimson star), plotted alongside a sample of *Swift*/BAT GRBs. Division between LGRBs (orange) and SGRBs (blue) is done automatically by *Swift*/BAT based on T_{90} duration of 2 seconds. Hybrid GRB events (black diamonds) are poorly classified using a purely duration based classification scheme, resulting in ambiguity in progenitor assessment. Both GRB 250221A and GRB 170817A (black star) lie in the ambiguous region between the GRB classes in this space, and within the wide spread of the hybrid GRBs.

4.1.2 Hardness ratio

Figure 5 shows the HR versus T_{90} diagram for *Swift*/BAT GRBs with GRB 250221A. The HR value is calculated using the fluence data from the *Swift*/BAT Gamma-Ray Burst Catalogue (Lien et al. 2016) power-law fit, taking the ratio of Band 3 (50 – 100 keV) over Band 2 (25 – 50 keV).

In the figure, GRB 250221A is indicated by a crimson star. We see that it lies between the peaks of the two distributions, outside the 2σ (95%-confidence) region for LGRBs but well within the corresponding region for SGRBs.

Additionally, other notable GRBs are shown in the figure for comparison. GRB 250221A lies close in the diagram to GRB 170817A, the GRB with the first and best observed KN counterpart. Both of these fall within the large distribution of the hybrid GRBs, which scatter widely in both T_{90} and HR, showing again the issue with duration-only classification.

4.1.3 Amati Correlation

Using the fluence estimated by *Swift*/BAT of $(3.9 \pm 0.6) \times 10^{-7} \text{ erg cm}^{-2}$, and the luminosity distance of 4.9 Gpc for the host galaxy, we estimate the isotropic energies and luminosities to be $E_{\text{iso}} = (1.1 \pm 0.2) \times 10^{51} \text{ erg}$ and $L_{\text{iso}} = (6.3 \pm 1.5) \times 10^{50} \text{ erg s}^{-1}$. Meanwhile, based on the time-averaged spectral analysis performed with the BATGRBPRODUCT tool over the interval $[-0.220, 1.844] \text{ s}$, the cutoff power-law peak energy, $E_p = 165.2 \text{ keV}$, translates into a rest-frame peak energy $E_{p,i}$ of 292.1 keV.

Figure 6 shows the resulting relations between the isotropic energy and intrinsic peak energy for GRB 250221A. These values are compared to those in the *Swift*/BAT GRB database. We distinguish between LGRBs (gray points) and SGRBs (blue points). The Amati relation for LGRBs (solid black line) and the 2σ (95%) confidence region of the Amati relation for GRBs (Amati et al. 2008; Amati & Della Valle 2013) are also shown. Redshift values are drawn from the

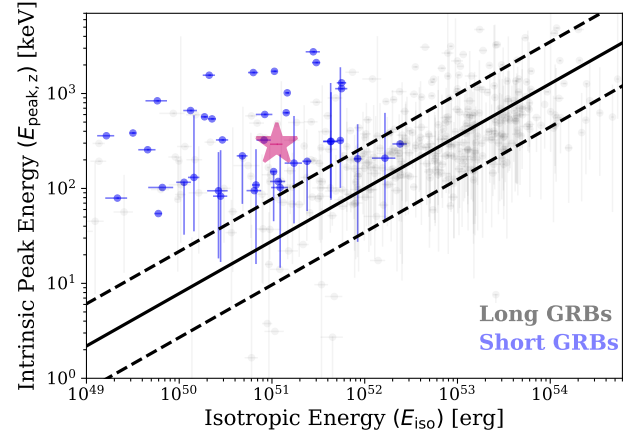


Figure 6. Isotropic energy and intrinsic peak energy for GRB 250221A (pink star). Long GRBs ($T_{90} > 2$ seconds) are shown in grey and short GRBs ($T_{90} < 2$ seconds) are shown in blue. The Amati relation, based on *Swift*/BAT GRBs with spectroscopic redshifts, is also shown (solid black line, Amati et al. 2008; Amati & Della Valle 2013). The 2σ confidence region of the relation is indicated by dashed lines.

Swift/BAT Gamma-Ray Burst Catalogue⁸, supplemented with spectroscopic measurements from Fong et al. (2022). At the redshifts of both candidate host galaxies, GRB 250221A falls outside the 95%-confidence region for LGRBs and aligns more closely with the short GRB population.

Finally, Frederiks et al. (2025) reported the detection of GRB 250221A with Konus-Wind. They observed the increase in the count rate in its 20–400 keV band from $T_0 - 1.5 \text{ s}$ to $T_0 + 4.4 \text{ s}$. Using a power-law with exponential cutoff (CPL) model, they estimate a fluence of $(1.67 \pm 0.09) \times 10^{-6} \text{ erg cm}^{-2}$ and a rest-frame peak spectral energy $E_{p,z}$ of $(428 \pm 44) \text{ keV}$.

We estimate the isotropic energies, the luminosities and the rest-frame peak energies for the host galaxy to be $E_{\text{iso}} = (4.6 \pm 2.6) \times 10^{51} \text{ erg}$, $L_{\text{iso}} = (1.6 \pm 0.9) \times 10^{51} \text{ erg s}^{-1}$ and $E_{p,z}$ of 427.9 keV. These values are consistent with the compact object merger progenitor (see Figure 13 from Tsvetkova et al. 2017).

4.2 Afterglow Model

Within the fireball model framework (Rees & Meszaros 1992; Meszaros & Rees 1993; Mészáros & Rees 1997), the afterglow emission originates from external shocks produced by the interaction of the relativistic jet with the surrounding circumstellar medium (Sari & Piran 1995; Sari 1997). Here we consider an ultra-relativistic, thin spherical shell, propagating inside an external medium with constant number density n . Initially, the shell is coasting with a bulk Lorentz factor (LF) $\Gamma_0 \gg 1$ and is slowed down by sweeping up the external medium in its path. This interaction gives rise to a double collisionless shock structure. A forward shock propagates ahead of the shell with $\Gamma_{\text{sh}} = \sqrt{2}\Gamma$ and shock-heats the swept up material that moves with bulk LF Γ behind it. A reverse shock propagates through the shell and extracts its kinetic energy while shock-heating the ejecta. When the mass of the swept up material exceeds M_0/Γ_0 , (where $M_0 = E_{k,\text{iso}}/(\Gamma_0 c^2)$ is the baryon load of the shell, $E_{k,\text{iso}}$ is

⁸ <https://swift.gsfc.nasa.gov/results/batgrbcatalog/>

its kinetic energy, and c the speed of light), the shell starts to decelerate. The subsequent dynamical evolution of the forward shock is given by the [Blandford & McKee \(1976\)](#) self-similar solution, with $\Gamma_{\text{sh}} \propto R^{-3/2}$. At this moment most of the kinetic energy of the shell is transferred to the shocked swept up material, resulting in a peak in the afterglow light curve and a power-law decline thereafter.

The forward shock accelerates a fraction of the electrons ($0 < \xi_e < 1$; [Eichler & Waxman 2005](#)) entering the shock into a power-law energy distribution, such that their comoving number density behind the shock is $n'_e(\gamma) \propto \gamma^{-p}$ for electrons with $\gamma \geq \gamma_m$ (where γ is the LF of the electrons and γ_m is the LF of minimal-energy electrons). The collisionless shock also compresses any pre-existing magnetic fields in the upstream medium and generates new magnetic fields in-situ. The relativistic electrons behind the shock cool by radiating broadband synchrotron radiation, which is described by a power-law that is broken smoothly at multiple characteristic frequencies ([Sari et al. 1998](#)). At late times, the afterglow emission is in the slow-cooling regime where the flux density, $F_\nu \propto T^\alpha \nu^\beta$, peaks at $\nu_m < \nu_c$, where T is the time in the observer frame and ν_m is the peak synchrotron frequency of minimal-energy electrons ([Granot & Sari 2002](#)). At higher frequencies ($\nu > \nu_m$) the spectrum breaks at the characteristic cooling-break frequency, ν_c , that corresponds to the peak synchrotron frequency of electrons cooling at the dynamical time. At frequencies $\nu_m < \nu < \nu_c$, the spectral index is $\beta = (1-p)/2$, while for $\nu > \nu_c$, it becomes $\beta = -p/2$. We interpret the observed afterglow radiation in this framework and use the known scaling relations ([Sari et al. 1998](#); [Granot & Sari 2002](#)) to constrain physical parameters.

The early ($T < 10^4$ s) optical and X-ray data can be modelled with simple power-laws having slopes $\alpha_o = -0.93 \pm 0.01$ and $\alpha_x = -0.97 \pm 0.04$, 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 $\nu_m < \nu < \nu_c$). Comparing the early optical decay slope $\alpha_o = -0.93 \pm 0.01$ with the expected one in a constant ambient density ($F \propto T^{3(1-p)/4}$), 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 ($F \propto T^{(1-3p)/4}$) would imply $p = 1.57 \pm 0.01$, an unusually low value for GRBs (see, e.g., [Zhang & Mészáros 2004](#); [Chevalier & Li 2000](#)).

Figure 7 presents the SED for the early emission phase of GRB 250221A, built using the data from *Swift*/XRT and COLIBRI, corresponding to an average photon arrival time of $T = 1800$ s for the XRT data. The optical flux densities for the early SED were interpolated from the light curve model described in Section 4.2, evaluated at the same epoch ($T = 1800$ s). The X-ray data were binned in groups of at most 10 bins with at least a 10σ significance. Two other epochs at $T = 9 \times 10^4$ s and $T = 1.8 \times 10^5$ s are also shown, and were taken directly from the light curve, as X-ray data were scarce at later times, and a time-sliced spectrum was not possible.

The first two epochs are well described by simple power-laws with spectral index $\beta = -0.71 \pm 0.03$ and $\beta = -0.85 \pm 0.01$, respectively. The third epoch, covering the peak of the rebrightening in optical and the apparent plateau in X-rays, is best described by two power-law segments: the first one going from the radio to optical energies, with a spectral index $\beta = -0.19 \pm 0.02$, the second one going from the optical to X-ray energies, with a spectral index $\beta = -0.91 \pm 0.04$.

Therefore, in a slow-cooling synchrotron regime, with an electron power-law index of $p = 2.24 \pm 0.01$, we obtain an optical spectral index of $\beta = (1-p)/2 = -0.62 \pm 0.01$. This value differs from the

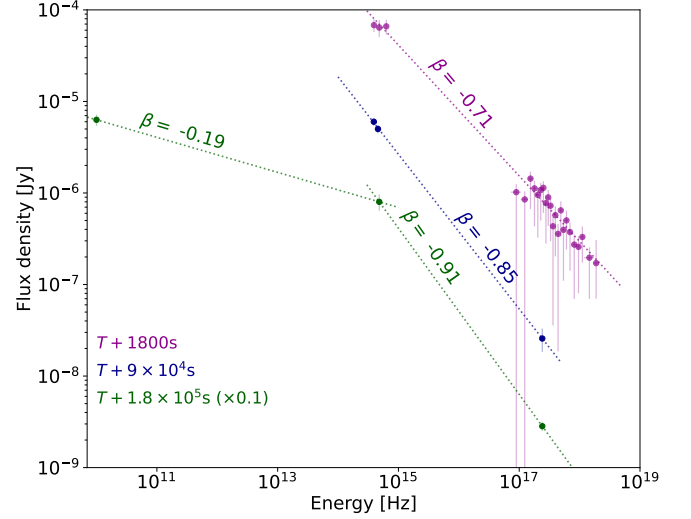


Figure 7. Evolution of the SED of GRB 250221A at three different epochs. The first epoch at an average time of $T_0 + 1800$ s (purple), the second epoch at $T_0 + 9 \times 10^4$ s (blue), and the third epoch at $T_0 + 1.8 \times 10^5$ s (green).

spectral fit $\beta = -0.71 \pm 0.03$ at $T + 1800$ s, that gives an electron power-law index of $p = 2.42 \pm 0.06$. The flux density for $\nu_m < \nu < \nu_c$ at time $T = T_1$ day is thus given by⁹

$$F_\nu \simeq 2.4 \times 10^{-3} \left(\frac{1+z}{1.768} \right)^{1.31} E_{k,\text{iso},52}^{1.31} n_{-1}^{0.5} \epsilon_{e,-1}^{1.24} \epsilon_{B,-3}^{0.81} T_{1\text{day}}^{-0.93} \quad (2)$$

$$\times \nu_{14}^{-0.62} d_{L,28.18}^{-2} \text{ mJy},$$

when assuming $\xi_e = 1$ and $z = 0.768$ with the corresponding luminosity distance of $d_L = 1.52 \times 10^{28}$ cm. Comparing this scaling relation with optical observations at $T = 1800$ s and $\nu = 4.81 \times 10^{14}$ Hz, with $F_\nu = 6.4 \times 10^{-2}$ mJy, allows us to constrain the kinetic energy,

$$E_{k,\text{iso}} = 1.67 \times 10^{52} n_{-1}^{-0.38} \epsilon_{e,-1}^{-0.95} \epsilon_{B,-3}^{-0.62} \text{ erg}, \quad (3)$$

in terms of fiducial parameters.

An additional constraint on $E_{k,\text{iso}}$ comes from the efficiency of the prompt γ -ray emission, $\eta_\gamma = [1 + (E_{k,\text{iso}}/E_{\gamma,\text{iso}})]^{-1} \gtrsim 15\%$ (e.g. [Beniamini et al. 2016](#)), which would limit the blast wave energy to $E_{k,\text{iso}} < [(1 - \eta_\gamma)/\eta_\gamma] E_{\gamma,\text{iso}} = 6.24 \times 10^{51}$ erg for if this level of efficiency was realized in this GRB.

A constraint on the interstellar medium (ISM) density can be obtained from the deceleration time of the blast wave, which also corresponds to the peak time of the afterglow light curve. The blast wave decelerates when the swept-up mass, $M_{\text{sw}}(R) = (4\pi/3)R^3 m_p n = M_0/\Gamma_0 = E_{k,\text{iso}}/\Gamma_0^2 c^2$, that yields, $R_{\text{dec}} = (3E_{k,\text{iso}}/4\pi m_p c^2 n \Gamma_0^2)^{1/3}$, where $\Gamma \simeq \Gamma_0$ is the coasting bulk LF of the ejecta at $R < R_{\text{dec}}$. The photon arrival time in the observer frame corresponding to emission produced at $R = R_{\text{dec}}$ is:

$$T_{\text{dec}} \simeq (1+z) \frac{R_{\text{dec}}}{2\Gamma_0^2 c} = (1+z) \left(\frac{3E_{k,\text{iso}}}{32\pi m_p c^5 n \Gamma_0^8} \right)^{1/3} \quad (4)$$

$$\simeq 429 \left(\frac{1+z}{1.768} \right) E_{k,\text{iso},52}^{1/3} n_{-1}^{-1/3} \Gamma_{0,2}^{-8/3} \text{ s}.$$

⁹ In this work we use the shorthand notation of $Q_n = Q/10^n$ for Q expressed in cgs units.

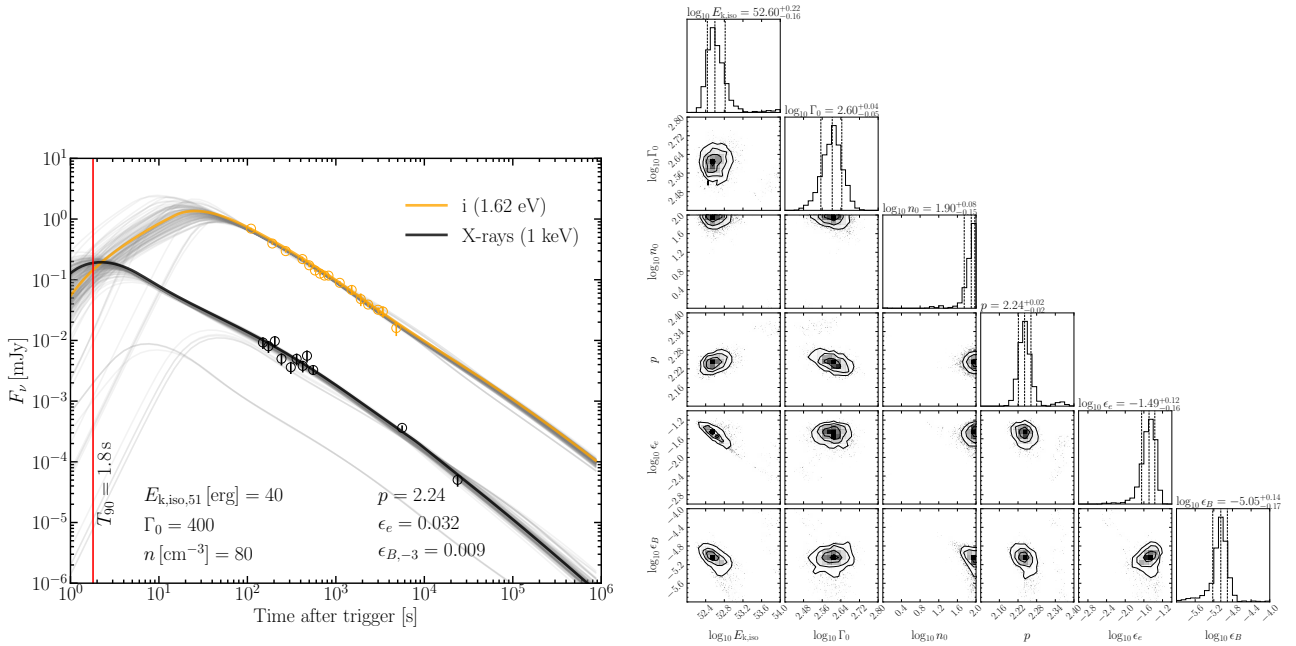


Figure 8. (Left) Afterglow model light curve fit to observations using the model from [Gill & Granot \(2018\)](#) that features a blast wave from a spherical shell moving in a ($k = 0$) constant density ISM. The 100 thin gray light curves are obtained from sampling the posterior distribution of model parameters, and the thick black and orange light curves are shown for model parameters that best fit the observations. The red vertical line shows the T_{90} duration of the prompt GRB. (Right) Model parameter posterior distributions obtained from an MCMC light curve fit.

Since the afterglow light curve shown in Figure 1 does not show a peak, the blast wave deceleration time must be $T_{\text{dec}} < 10^2$ s. We use this constraint along with Equation (3), to constrain the ISM density in terms of the shock microphysical parameters, with $n > n_{\text{min}}$,

$$n_{\text{min}} = 2.1 \epsilon_{e,-1}^{-0.69} \epsilon_{B,-3}^{-0.45} \Gamma_{0,2}^{-5.79} \text{ cm}^{-3} \quad (5)$$

assuming that $\Gamma_0 = 100$, which is the minimum LF needed for an on-axis burst to overcome the compactness problem and emit a GRB. SGRBs are typically found with significant offsets from the centers of their respective host galaxies, with 50 percent showing an offset in excess of 5 kpc (e.g. [Fong & Berger 2013](#); [O'Connor et al. 2022](#)). The ISM density is then expected to be low with $10^{-3} \lesssim n(\text{cm}^{-3}) \lesssim 1$ ([Berger 2014](#); [O'Connor et al. 2020](#)).

The optical band is above the peak synchrotron frequency of the minimal energy electrons, which is given by [Granot & Sari \(2002\)](#) as

$$\nu_m = 6.43 \times 10^{10} (1+z)^{1/2} E_{k,\text{iso},52}^{1/2} \epsilon_{e,-1}^2 \epsilon_{B,-3}^{1/2} T_{1\text{ day}}^{-3/2} \text{ Hz}, \quad (6)$$

and this constraint gives a weak lower limit on $\epsilon_B > \epsilon_{B,\text{min}}$,

$$\epsilon_{B,\text{min}} = 1.8 \times 10^{-10} \epsilon_{e,-1}^{-1.53} \Gamma_{0,2}^{4.94}. \quad (7)$$

An additional constraint on ϵ_B can be obtained from noting that $\nu_c > \nu_X = 10$ keV, where

$$\nu_c = 2.68 \times 10^{17} (1+z)^{-1/2} E_{k,\text{iso},52}^{-1/2} n_0^{-1} \epsilon_{B,-3}^{-3/2} T_{1\text{ day}}^{-1/2} \text{ Hz}, \quad (8)$$

which yields $\epsilon_B < \epsilon_{B,\text{max}}$,

$$\epsilon_{B,\text{max}} = 3.1 \times 10^{-4} \epsilon_{e,-1}^{1.24} \Gamma_{0,2}^{5.65}. \quad (9)$$

The available data is not able to put strong constraints on the model parameters. To understand the spread in the values of the different parameters, we perform a light curve fit to the optical ($\nu_O = 3.93 \times 10^{14}$ Hz) and X-ray ($\nu_X = 2$ keV) data using Markov-chain Monte-Carlo (MCMC) methods and a model of a spherical

blast wave propagating in a constant density ISM ($k = 0$) from [Gill & Granot \(2018\)](#). The fit is obtained using the data before the re-brightening episode at $T \lesssim 3 \times 10^4$ s and the results are shown in Figure 8.

The MCMC fit finds an ultrarelativistic blast wave with a coasting bulk LF of $\Gamma_0 \sim 400$ and an isotropic-equivalent kinetic energy of $E_{k,\text{iso}} \gtrsim 10^{52}$ erg. Given that the radiated isotropic-equivalent energy in γ -rays is around $E_{\gamma,\text{iso}} \sim 10^{51}$ erg, it yields a γ -ray efficiency of $\eta_\gamma \lesssim 10\%$. The fit also demands the jet moves in a dense environment with ISM density $n \gtrsim 80 \text{ cm}^{-3}$, which is large for a binary merger scenario (e.g. [O'Connor et al. 2020](#); [Fong et al. 2015](#)) and more in line with Collapsar produced long GRBs. The fit also finds the peak time of the afterglow, and hence the deceleration time to be $T_{\text{dec}} \sim T_{90}$ as can be inferred from the peak of the X-ray afterglow; the optical light curve shows a delayed peak due to the passage of $\nu_m \propto T^{-3/2}$ across the optical band.

4.3 Nature and Progenitor of GRB 250221A

The properties of the GRB environment, such as its redshift, offset from the host galaxy and evidence for star-formation (see Figure 3), are consistent with both long and short GRBs. However, based on its duration, temporal evolution, the presence of a single sharp spike in the prompt emission, its peak energy, and its position in the Amati correlation, the properties of GRB 250221A fall within the typical range expected for SGRBs ([Berger 2014](#)). These considerations suggest that GRB 250221A may have originated from the coalescence of two compact objects.

Nevertheless, the atypically large ISM density required by the afterglow modelling (Section 4.2) appears more in line with a Collapsar exploding within its dense progenitor cloud.

If this was the case, the event would lie at the extreme end of the

LGRB population in terms of T_{90} , hardness ratio, and peak energy. We will further explore this possibility in the following sections.

5 ORIGIN OF OPTICAL REBRIGHTENING

Figure 1 shows evidence for a change in the fading evolution and a rebrightening at $T > 0.6$ d. In this section, we explore and discuss possible scenarios that could account for this. Given the ambiguity surrounding the origin of the event, we first consider whether the observed excess can be explained by a supernova associated with the death of a massive star (Section 5.1), then we turn to scenarios related to the host galaxies and the surrounding environment, including the possibility of gravitational microlensing (Section 5.2) or density variations in the CBM (Section 5.3). Finally, we investigate whether the excess could be produced by a refreshed shock within the main jet of GRB 250221A (Section 5.4).

Scenarios involving kilonova origin for the optical excess can be ruled out. An AT2017gfo-like (Abbott et al. 2017) event placed at $z = 0.768$ would appear at $r \sim 28.6$ mag, far below our detection limits. Even the brightest magnetar-powered kilonova models are undetectable at this distance (see e.g. Metzger et al. 2010; Metzger & Berger 2012). Similarly, a fast blue optical transient (FBOT) (see e.g. Perley et al. 2019, 2021) origin is very unlikely. While these transients reach high luminosities and rise rapidly, the observed negative spectral slopes ($\beta < 0$) of the afterglow of GRB 250221A are inconsistent with the expected blue continua of FBOTs ($\beta > 0$). Thus, neither a kilonova nor an FBOT provides a plausible explanation for the excess emission.

5.1 Supernova

Firstly, we consider the case where the GRB 250221A event resulted from the collapse of a rapidly rotating, stripped-envelope massive star (Woosley 1993), in which case one might think that the late optical excess observed after $T_0 + 0.6$ d could be attributed to the emergence of an underlying supernova.

Broad-lined Type Ic SNe, have been associated with LGRBs through both temporal and spatial coincidence, as well as spectroscopic confirmation (see e.g. Galama et al. 1998; Hjorth et al. 2003; Pian & Mazzali 2006; Mirabal et al. 2006; Becerra et al. 2017). These SNe usually present peak absolute magnitudes of $M_V \approx -19$ to -20 around 10 to 15 days after the burst in the rest frame (e.g. Cano et al. 2017). This timescale is determined by the radioactive decay of ^{56}Ni and ^{56}Co .

At the luminosity distance of $d = 4.9$ Gpc, standard type Ibc supernovae (SN 1998bw-like; Galama et al. 1999) would exhibit apparent peak magnitudes in the range of $\sim 24.5.0-25.5$, making them several orders of magnitude fainter than the late-time component observed in GRB 250221A. On the other hand, a very luminous supernova associated with a magnetar such as SN2011kl could be brighter by about one magnitude Greiner et al. (2015) and therefore comparable with the values exhibited for GRB 250221A in the rebrightening.

However, the excess exhibited by GRB 250221A emerges on timescales of hours rather than the typical rise time of several days expected for supernovae (Cano et al. 2017). This discrepancy in both luminosity and temporal behaviour renders a supernova origin an unlikely explanation for the late-time photometric evolution of the transient (see Figure 1).

5.2 Gravitational Microlensing

It is tempting to associate the rebrightening with a microlensing event, assuming that G2 is the host and G1 is a galaxy on the line-of-sight. In the following, we briefly describe the formalism for GRB microlensing first introduced by Loeb & Perna (1998). As discussed in section 4.2, the temporal evolution of the spherical blast wave is described by the Blandford & McKee (1976) self-similar solution, with $\Gamma \propto R^{-3/2}$, after it has been decelerated by its interaction with the ISM.

The afterglow image on the plane of the sky is predicted to appear as a ring with a narrow fractional width, W , that depends on the observed frequency and whose radius grows with apparent time T as a power law, with $R_s(T) \propto R/\Gamma \propto R^{5/2} \propto T^{5/8}$ where $R \propto \Gamma^2 T \propto T^{1/4}$. In the optical band, W is predicted to be of the order of a few percent (Loeb & Perna 1998; Granot et al. 1999). After about a day after the trigger, the radius of the ring, $R_s(T) \approx 1.1 \times 10^{17} E_{k,iso,52}^{1/8} n_1^{-1/8} T_{day}^{5/8}$ cm (Piran 1999), becomes comparable to the Einstein radius of a solar mass lens, $r_E = \sqrt{(4GM/c^2)(D_L D_{LS}/D_S)}$ where D_L , D_{LS} , and D_S are the lens-observer, lens-source and source-observer angular distances, respectively, M is the mass of the lens.

The magnification of a uniform ring of fractional width W and impact factor b is given by Loeb & Perna 1998,

$$\mu(R_s, W, b) = \frac{\Psi(R_s, b) - (1-W)^2 \Psi[(1-W)R_s, b]}{1 - (1-W)^2}, \quad (10)$$

where $\Psi(R_s, b)$ is the magnification of a uniform disk of radius R_s ,

$$\Psi(R_s, b) = \frac{2}{\pi R_s^2} \left[\int_{|b-R_s|}^{b+R_s} dR \frac{R^2 + 2}{\sqrt{R^2 + 4}} \arccos \frac{b^2 + R^2 - R_s^2}{2Rb} + H(R_s - b) \frac{\pi}{2} (R_s - b) \sqrt{(R_s - b)^2 + 4} \right], \quad (11)$$

and $H(x)$ is the Heaviside step function. The lensed flux is given by $F_\nu^{\text{lensed}}(T) = \mu[R_s(T), W, b] F_\nu(T)$.

So, assuming that the lens is in G1 and the GRB is in G2, we get $D_L \approx 1037$ Mpc, $D_{LS} \approx 783$ Mpc, and $D_S \approx 1571$ Mpc, respectively (Planck Collaboration et al. 2020) and hence, $r_E \approx 3.1 \times 10^{16} (M/M_\odot)^{1/2}$ cm. Since the radius of the ring depends on the kinetic energy and the density of the medium, we adopt here a range of values around the values shown in Figure 8. We find that for the following ranges $1 \lesssim n_1 \lesssim 5$ and $0.1 \lesssim E_{k,iso,52} \lesssim 10$, the timescale for the excess demands $b < 1$ and $M \sim 50 M_\odot$. The width of the excess demands a fractional width of the ring $W \sim 0.1$. However, this modelling does not allow accounting for the amplitude of the excess, as can be seen in Figure 9. We note that these microlensing calculations are done considering a uniform ring for the afterglow image (Loeb & Perna 1998).

5.3 ISM Local Density Enhancement

As we describe in Section 4.2, the fireball model describes the afterglow emission as a smooth light curve that can be modelled with power-law segments. However, in reality, light curve variability is observed in several GRBs (Nakar et al. 2003; de Ugarte Postigo et al. 2005), and can be attributed to an increase in external density that the fireball interacts with, experiencing additional deceleration (Nakar & Granot 2007).

In the case of LGRBs, which are predominantly found in star-forming galaxies (Perley et al. 2016), variations in the external density profile may arise due to several factors. These include the presence of

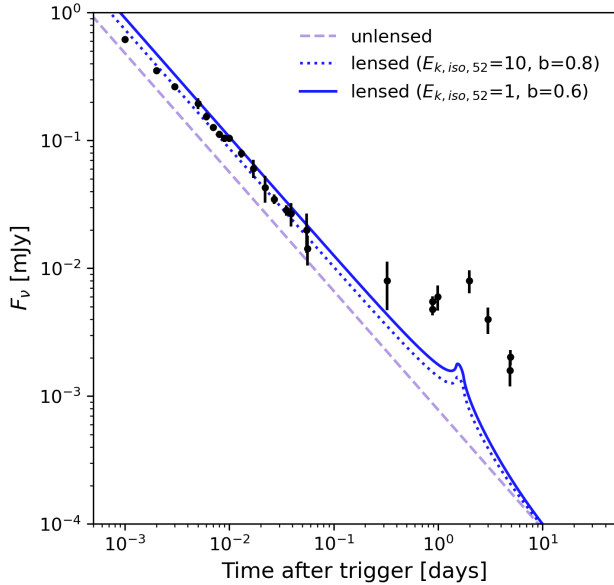


Figure 9. Unlensed (dashed line) and lensed flux from a GRB afterglow with $b = 0.6$, $E_{k,iso,52} = 1$ (solid line, corresponding to a magnification of ~ 3.5) and $b = 0.8$, $E_{k,iso,52} = 10$ (dotted line, corresponding to a magnification of ~ 2.7) at a frequency of $\sim 4.8 \times 10^{14}$ Hz (optical data; black points). The density is $n_1 = 5$. The fractional width of the emission ring is $W=10\%$. The lens mass is $M = 50 M_\odot$, and its redshift is 0.343. The source redshift is 0.768.

massive stellar winds, the transition between the low-density bubble created by the stellar wind and the outer molecular cloud, and density structures within the molecular cloud itself. The interaction of the relativistic jet with such inhomogeneities could produce variability in the afterglow light curve, potentially as early as $T \sim 1$ day post-burst (Tam et al. 2005).

In contrast, for SGRBs, and likely GRB 250221A, this explanation does not apply. Their compact-object progenitors merge long after both stars have exploded as supernovae, leaving behind a CBM free of stellar-wind disturbances. Thus, any external density variations must stem from inhomogeneities in the ISM (Nakar & Granot 2007).

Nevertheless, Nakar & Granot (2007) demonstrated that density fluctuations in the external medium have a minimal impact on the forward shock emission as the dynamics of the relativistic blast wave tend to suppress any resulting re-brightening. Furthermore, van Eerten et al. (2009) performed hydrodynamical simulations of a relativistic blast wave interacting with a wind termination shock, finding no significant variability in the optical light curve, even in the presence of large density contrasts. Therefore, these results favour scenarios involving refreshed shocks or multiple ejection episodes as more plausible explanations for the observed variability.

5.4 Refreshed Shock

5.4.1 Reverse Shock Emission from Two-Shell Collision

To explain the rebrightening of the afterglow emission around starting from $T_0 \sim 1$ day (hereafter T_{bright}), we first consider a scenario where a second (inner) shell of mass emitted by the central engine, with some delay of t_{em} in the engine frame, catches up from behind with the decelerating first (outer) shell and refreshes the shock by

injecting more energy (e.g. Kumar & Piran 2000; Sari & Mészáros 2000; Zhang & Mészáros 2002; Vlasov et al. 2011). We develop the model of two spherical shell collision in Appendix (A), where we calculate characteristic radii, timescales, and dynamics of the system (also see, e.g., Anderson et al. 2025). As the two shells collide (see Figure A1) a forward shock (FS) propagates into the outer shell and a reverse shock (RS) propagates into the inner shell. The shock jump conditions at the two shocks are different, as the outer shell is already relativistically hot while the inner shell is cold. The main parameters in the problem include the ratio of the kinetic energies of the two shells ($E_{k,iso,6}/E_{k,iso,3}$), the ratio of their initial bulk Lorentz factors ($\Gamma_{0,3}/\Gamma_{0,6}$), and the shock microphysical parameters at the two shocks.

In the case of a binary merger, the two shells must be emitted with negligible delay, such that $t_{\text{em}} \ll T_{90}$, and therefore the inner shell must have $\Gamma_{0,6} < \Gamma_{0,3}$. This condition also guarantees that the inner shell must be spreading radially before the collision, i.e. it is in the thin-shell regime. Also, in general, if $t_{\text{em}} \ll T_{\text{bright}}$, then the ratio of the initial bulk Lorentz factors is fixed (see Equation A2), such that

$$\frac{\Gamma_{0,3}}{\Gamma_{0,6}} \approx \frac{[4(T_{\text{bright}}/T_{\text{dec}})]^{3/8}}{2} \quad (12)$$

$$\approx 56 \left(\frac{1+z}{1.768} \right)^{-3/8} E_{k,iso,52.6}^{-1/8} n_{1.9}^{1/8} T_{\text{bright},4.8}^{3/8} \quad (\text{G2}).$$

Since $\Gamma_{0,3} \sim 400$ is obtained from the MCMC fits, this yields $\Gamma_{0,6} \sim 8$. Figure A2 shows the dynamical evolution of the different shocked and unshocked regions, where we find that the RS remains non-relativistic as it crosses the inner shell, as expected for a thin shell.

As shown in Zhang & Mészáros (2002), the RS emission typically dominates over that coming from the other two shocked regions before it declines rapidly. The shock jump conditions in Equation A5 yield the energy and number density of the shocked medium, which we then use to calculate the characteristic synchrotron frequencies and the peak flux (e.g. Sari et al. 1998; Gill & Granot 2018). In calculating the observed emission, we simplify to obtain radiation emitted only along the LOS without performing EATS integration, with photon arrival time given by $T = (1+z)R/4\Gamma^2 c$.

Figure 10 shows the RS emission (dashed) from the inner shocked shell in addition to that produced at the FS (dotted) from the outer shell. The RS emission rises to a peak that marks the instant when the shock finishes crossing the inner shell. After RS passage, the shock is no longer active and no newly accelerated particles are being injected behind the shock. Therefore, the emission declines and also cuts off for $\nu > \nu_{\text{cut}}$ (Kobayashi 2000), which affects the X-rays first and then the optical at a later time, where both show a sudden drop in the light curve. In reality, the light curve does not drop so suddenly as emission from angles away from the LOS still arrives with an angular delay of $T_\theta \simeq (1+z)R/4\Gamma^2 c \simeq 1.3 \times 10^5 (1+z) R_{17.6} \Gamma_{0,7}^{-2}$ s, causing the light curve to be smeared over this timescale. Nevertheless, this model has a drawback: it overproduces the radio emission by approximately an order of magnitude compared to the observations (see Figure 10). We will investigate this apparent disagreement in the next section.

The two shell collision scenario, as described here, demands a significantly large amount of energy to be residing in the inner shell. In this case $E_{k,iso,6}/E_{k,iso,3} \simeq 20$, which for $\Gamma_{0,6} \sim 8$ implies a large density in the inner shell compared to the outer one. Since the RS is non-relativistic, large densities are needed to obtain a bright emission. When such a large amount of energy is injected into the blast wave, it should also lead to very bright FS emission (not calculated in this model) after the RS emission fades, which would significantly overproduce the emission during the decaying phase of

the rebrightening episode. Therefore, this model is disfavoured by the observations.

5.4.2 Energy Injection into the Forward Shock of a Jet

Next we consider an alternative model with continuous energy injection into the blast wave produced by a jet. Two different ways of doing so have been discussed in the literature for a spherical flow, where (i) the ejecta comprises a radial velocity stratification, with progressively slower moving inner shells trailing behind the faster outer shell (Rees & Mészáros 1998; Sari & Mészáros 2000), or (ii) a rapidly spinning central engine, e.g. a millisecond magnetar, continuously injects energy into the blast wave via a magneto-hydrodynamical (MHD) wind as it spins down (Dai & Lu 1998a,b; Zhang & Mészáros 2001, 2002). 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. Both scenarios have been used in many earlier works (e.g., Laskar et al. 2018; Schroeder et al. 2024; de Wet et al. 2024; Schroeder et al. 2025) to explain rebrightening features in afterglow light curves, with the assumption that the trailing ejecta in model (i) only catches up with the faster moving blast wave at the time of the rebrightening.

Here we consider energy injection over a narrow radial width $\Delta R = R_2 - R_1$, where injection commences at radius R_1 and ceases at R_2 . Total energy E_{inj} is injected as a power-law in radius at the rate

$$\frac{dE}{dR} = \frac{(1+\ell)}{\Delta R} E_{\text{inj}} \left(\frac{R-R_1}{\Delta R} \right)^\ell \propto R^\ell, \quad (13)$$

so that the energy of the blast wave grows as $E(R) \propto R^{1+\ell}$. From energy conservation in the blast wave (Blandford & McKee 1976; Chiang & Dermer 1999; Huang et al. 1999; Zhang & Mészáros 2002), we get

$$E_{\text{inj}} + (\Gamma_0 - \Gamma) M_0 c^2 = (\Gamma^2 - 1) M_{\text{sw}} c^2, \quad (14)$$

where M_0 and M_{sw} are the masses of the ejecta and swept-up external medium, which simplifies to the known result of $E_{\text{k,iso}} = \Gamma_0 M_0 c^2 = \Gamma^2 M_{\text{sw}} c^2$ for $\Gamma_0 \gg \Gamma$ and $\Gamma \gg 1$ in the absence of energy injection. When E_{inj} dominates over $E_{\text{k,iso}}$, the above equation simplifies further to $E_{\text{inj}} \sim \Gamma^2 M_{\text{sw}} c^2 \propto \Gamma^2 R^3$ for an ISM external medium. This yields the scaling $\Gamma(R) \propto R^{(\ell-2)/2}$, and since $R \propto \Gamma^2 T$, the apparent time scales with radius as $T \propto R^{3-\ell}$, which yields $E_{\text{inj}} \propto T^{(1+\ell)/(3-\ell)}$.

To solve for the dynamical evolution of the spherical blast wave with energy injection, we use the numerical code of Gill & Granot (2023) that produces EATS-integrated afterglow emission. Figure 11 shows the afterglow light curve where we take the best-fit solution from Figure 8 and inject $E_{\text{inj}} \simeq 4.5 E_{\text{k,iso}}$ into the blast wave with $\ell = 0.6$. During the energy injection phase, the light curves for the radio ($\nu_m < \nu_R < \nu_a < \nu_c$), optical ($\nu_a < \nu_O < \nu_c$), and X-rays ($\nu_c < \nu_X$) show distinct temporal trends since all three are located on different power-law segments of the synchrotron spectrum. Here ν_m and ν_c are the characteristic injection and cooling-break frequencies, as defined earlier, and ν_a is the self-absorption frequency. Since the radio emission is self-absorbed, the rebrightening shows a temporal lag of $\Delta T \sim 4$ days with respect to that seen in optical and X-rays.

To explain the late-time radio and X-ray emission, a jet break in the light curve at $T \sim 10^5$ s is required, with a jet half-opening angle of $\theta_j = 11.5^\circ$. An on-axis ($\theta_{\text{obs}} = 0$) observer would see a jet break in the afterglow light curve when the angular size of the beaming cone around the line-of-sight exceeds the opening angle of the jet, i.e.

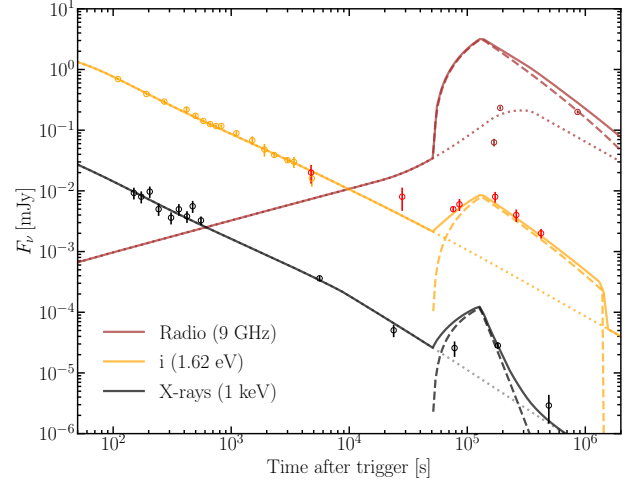


Figure 10. Best-fit light curve as obtained in Figure 8 (dotted), now with the addition of reverse shock emission arising from the two spherical shell collision (dashed), with the sum of the two emissions shown with a solid line. The shock-microphysical parameters for the emission from the refreshed shock are $\epsilon_e = 0.04$ and $\epsilon_B = 3 \times 10^{-5}$ with $p = 2.1$.

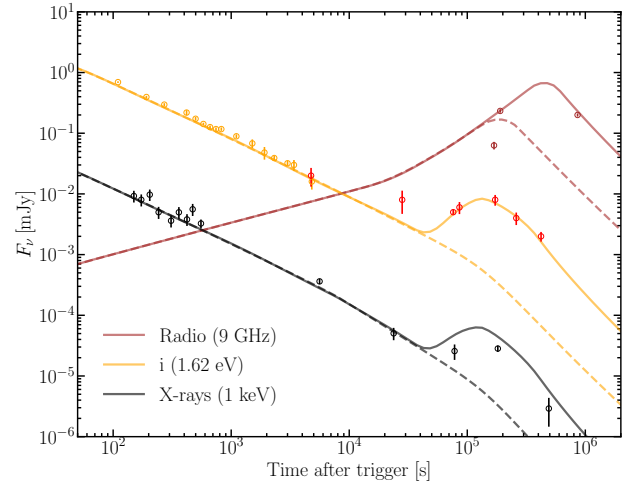


Figure 11. Best-fit light curve as obtained in Figure 8 (dashed), now with energy injection (solid) into a jet with half-opening angle $\theta_j = 11.5^\circ$. The injected energy is $E_{\text{inj}} = 4.5 E_{\text{k,iso}}$, with $R_1 = 1.3 \times 10^{17}$ cm, $R_2 = 1.82 R_1$, $\ell = 0.1$, and $\epsilon_e = 0.027$, $\epsilon_B = 10^{-5}$.

when $1/\Gamma = \theta_j$, which would occur at the time $T_j = (\Gamma_0 \theta_j)^{8/3} T_{\text{dec}} \simeq 2 \times 10^5$ s for $\Gamma_0 = 400$ and $T_{\text{dec}} \simeq 2$ s. The true jet kinetic energy in this scenario can be estimated from the total isotropic-equivalent energy, with $E_k \simeq (\theta_j^2/2) E_{\text{k,iso,tot}} = 4.4 \times 10^{51}$ erg where $E_{\text{k,iso,tot}} \simeq 5.5 E_{\text{k,iso}}$, and $E_{\text{k,iso}}$ is the energy of the fastest moving material.

This model is able to explain both the optical data during the rebrightening phase quite well, but mildly overproduces the X-ray emission while maintaining the correct temporal decay trend. The reason for this discrepancy may lie in the assumption of fixed shock microphysical parameters over the entire duration of the afterglow. Energy injection may break this assumption and require different shock microphysical parameters during the rebrightening episode.

The model also overproduces the radio emission at the time of the first detection. The sharp rise in the observed radio emission over $\Delta T \sim 2.2 \times 10^4$ s is difficult to reproduce in this model. As discussed in the previous section, the angular delay time over which any sharp pulse gets smeared is $T_\theta \sim 10^5$ s when $T \sim 10^5$ s, so that $\Delta T/T \sim 1$. Therefore, the radio emission is not expected to rise so sharply over $\Delta T/T \ll 1$ during the afterglow.

In the first scenario, where the ejecta has a radial gradient in velocity, so that the mass above a given bulk- Γ scales as $M(> \Gamma) \propto \Gamma^{-s}$ (Rees & Mészáros 1998; Sari & Mészáros 2000), the energy in the blast wave grows as $E(> \Gamma) \propto \Gamma^{1-s} \propto T^{-\frac{3(1-s)}{(7+s)}}$ after the fastest moving material decelerates. The scaling of the blast wave energy with T in this model corresponds to $s = (4 + \ell)/(2 - \ell) \simeq 2.2$. Since $s > 1$, both the mass and energy in the ejecta are dominated by the slower moving material. In the second scenario, energy is injected by the spinning down magnetar with power $L(T) \propto T^q$, where the blast wave energy grows as $E \propto T^{1+q}$ (Zhang & Mészáros 2001). Comparison of this scaling with our model gives $q = 2(\ell - 1)/(3 - \ell) = -0.62$.

6 SUMMARY & DISCUSSION

We have presented multi-wavelength observations of the short duration GRB 250221A obtained with COLIBRÍ, the Harlingen 50 cm Telescope, VLT, and VLA from 1 hour after the burst up to 11 days later. We have supplemented our data with public data from *Swift*/BAT, *Swift*/XRT, *Einstein Probe*/FXT and photometry from the Legacy Survey catalogue DR10 (Dey et al. 2019).

Deep imaging shows the presence of two candidate host galaxies in the field of GRB 250221A. Our analysis of the X-Shooter afterglow spectrum firmly places the event at a redshift $z = 0.768$ in a galaxy with evidence of star formation.

The light curve shows a typical decay in the optical and X-ray frequencies before $T < 10^4$ s for synchrotron emission, with the characteristic frequencies being $\nu_m \lesssim \nu_{\text{opt}} \lesssim \nu_X \lesssim \nu_c$ indicating a slow-cooling synchrotron regime in a circumstellar profile of constant density. At later times, after $T \sim 0.6$ d, we observe an excess in the X-ray, optical, and radio light curves.

We have ruled out several scenarios to explain this excess, including a supernova, gravitational microlensing, and a local density enhancement.

The direct observational evidence, particularly the short duration, peak energy and hardness ratio as well as the Amati correlation more strongly supports a merger-driven coalescence scenario as the progenitor channel for GRB 250221A. Nevertheless, the best fit parameters obtained for the afterglow model before the refreshed shock component suggest a high-density environment, which is more consistent with a Collapsar scenario.

Regardless, the central engine can be argued to be either a millisecond magnetar (Metzger et al. 2011) or a hyperaccreting black hole (BH) (MacFadyen & Woosley 1999b) that should be able to provide a total energy $E_{\text{tot}} = E_k + E_\gamma \approx E_k = 4.5 \times 10^{51}$ erg to power the GRB and its afterglow. In the Collapsar scenario, the total duration over which the outflow is powered is obtained from $t_{\text{jet}} = t_{\text{bo}} + T_{90}/(1 + z) \sim 10$ s where we take $t_{\text{bo}} \sim 9$ s for the jet to break out of the stellar progenitor (Bromberg & Tchekhovskoy 2016). The mean jet power that the engine must be able to provide is $L_{\text{jet}} = E_{\text{tot}}/\eta_j t_{\text{jet}} \sim 4.5 \times 10^{51} \eta_{j,-1}^{-1} t_{\text{jet},1}^{-1} \text{ erg s}^{-1}$ for an assumed efficiency of $\eta_j = 0.1 \eta_{j,-1}$. In the case of a binary merger of two NSs, the jet breakout time out of the dynamical ejecta is $t_{\text{bo}} \sim 0.5$ s (e.g., Moharana & Piran 2017; Gill et al. 2019), which would demand a

mean jet power $L_{\text{jet}} \sim 3 \times 10^{52} \eta_{j,-1}^{-1} (t_{\text{jet}}/1.5 \text{ s})^{-1} \text{ erg s}^{-1}$. The total energy and mean jet power in this event can be supplied by any of the various known jet launching mechanisms, namely $\nu\bar{\nu}$ annihilation from accretion onto a NS or BH (see, e.g. MacFadyen & Woosley 1999b; Zalamea & Beloborodov 2011; Globus & Levinson 2014), an MHD wind from a millisecond magnetar (Metzger et al. 2011), a Kerr BH with a Blandford-Znajek engine (Blandford & Znajek 1977; Brown et al. 2000), or a Schwarzschild/Kerr BH with a BP engine (Blandford & Payne 1982).

We attribute the rebrightening in the afterglow light curve at $T > 0.6$ days to energy injection by the central engine into the forward shock produced by a relativistic jet. Three popular scenarios of energy injection in which a single and isolated rebrightening episode is realized are refreshing of the forward shock due to a mild collision (as opposed to a violent one) between two matter shells (Kumar & Piran 2000), the ejecta having a radial velocity stratification (Rees & Mészáros 1998; Sari & Mészáros 2000), or energy injected by a spinning down millisecond magnetar via an MHD wind (Zhang & Mészáros 2001). In all of these three scenarios, the energy of the blast wave is gently increased without the formation of strong shocks propagating through both the initial blast wave and energizing material. The main result is an increase in the emission from the forward shock produced by the initial blast wave. Alternatively, a millisecond-magnetar central engine can power the initial jet, and energy can be later injected into it by the gravitational collapse into a Schwarzschild BH as the magnetar spins down and loses centrifugal support, thus releasing the remaining binding energy $E_B \simeq 5 \times 10^{53}$ erg (see Moreno Méndez et al. 2015, for further discussion and details on this model; see also Appendix B).

The complete multi-wavelength photometric follow-up and modelling of GRB 250221A provide key insights into its progenitor, central engine, and energy injection mechanisms, while afterglow spectroscopy proved crucial for characterizing the CBM of this short-duration burst. Together, these observations add to the growing number of long and short GRBs that exhibit rebrightening episodes in their afterglows, commonly attributed to refreshed shocks and late-time central engine activity (e.g. Granot et al. 2003; Fan & Xu 2006; Soderberg et al. 2006; de Ugarte Postigo et al. 2007; Troja et al. 2007; Rowlinson et al. 2013; Hascoët et al. 2012; Laskar et al. 2015, 2018; Lamb et al. 2019; de Wet et al. 2023; Moss et al. 2023; de Wet et al. 2024; Schroeder et al. 2024, 2025). The case of GRB 250221A demonstrates how coordinated, multi-wavelength follow-up and prompt spectroscopy can reveal new facets of GRB physics and challenge our current understanding of their progenitors.

ACKNOWLEDGEMENTS

We thank Antonio Castellanos-Ramírez for his useful comments.

We thank the staff of the Observatorio Astronómico Nacional on Sierra San Pedro Mártir.

Some of the data used in this paper were acquired with the DDRAGO instrument on the COLIBRÍ telescope at the Observatorio Astronómico Nacional on the Sierra de San Pedro Mártir. COLIBRÍ and DDRAGO are funded by the Universidad Nacional Autónoma de México (CIC and DGAPA/PAPIIT IN109418 and IN109224), and SECITI/CONACyT (277901, Ciencias de Frontera 1046632 and Laboratorios Nacionales). COLIBRÍ received financial support from the French government under the France 2030 investment plan, as part of the Initiative d'Excellence d'Aix-Marseille Université-A*MIDEX (ANR-11-LABX-0060 – OCEVU and AMX-19-IET-008 – IPHu), from LabEx FOCUS (ANR-11-LABX-0013), from the

CSAA-INSU-CNRS support program, and from the International Research Program ERIDANUS from CNRS. COLIBRÍ and DDRAGO are operated and maintained by the Observatorio Astronómico Nacional and the Instituto de Astronomía of the Universidad Nacional Autónoma de México.

This work made use of data supplied by the UK *Swift* Science Data Centre at the University of Leicester.

Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO program 1114.D-0276(M).

The National Radio Astronomy Observatory and Green Bank Observatory are facilities of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

This work is based on the data obtained with Einstein Probe, a space mission supported by the Strategic Priority Program on Space Science of Chinese Academy of Sciences, in collaboration with the European Space Agency, the Max-Planck-Institute for extraterrestrial Physics (Germany), and the Centre National d'Études Spatiales (France).

CAV acknowledges support from a SECIHTI fellowship.

RLB, RR, ET, MY and YY acknowledge support from the European Research Council through the Consolidator grant BHianca (grant agreement ID 101002761).

AMW is grateful for support from UNAM/DGAPA project IN109224.

NG and LGG gratefully acknowledge the support of the Simons Foundation (MP-SCMPS-00001470, N.G., L.G.G.).

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

- Abbott B. P., et al., 2017, *ApJ*, **848**, L13
- Agüí Fernández J. F., et al., 2023, *MNRAS*, **520**, 613
- Ahumada T., et al., 2021, *Nature Astronomy*, **5**, 917
- Amati L., Della Valle M., 2013, *International Journal of Modern Physics D*, **22**, 1330028
- Amati L., Guidorzi C., Frontera F., Della Valle M., Finelli F., Landi R., Montanari E., 2008, *MNRAS*, **391**, 577
- Anderson G. E., et al., 2025, *arXiv e-prints*, p. [arXiv:2508.14650](https://arxiv.org/abs/2508.14650)
- Atteia J. L., et al., 2017, *ApJ*, **837**, 119
- Basa S., et al., 2022, in Marshall H. K., Spyromilio J., Usuda T., eds, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 12182, Ground-based and Airborne Telescopes IX*. p. 121821S, [doi:10.1117/12.2627139](https://doi.org/10.1117/12.2627139)
- Becerra R. L., et al., 2017, *ApJ*, **837**, 116
- Becerra R. L., et al., 2019a, *ApJ*, **872**, 118
- Becerra R. L., et al., 2019b, *ApJ*, **881**, 12
- Becerra R. L., et al., 2023, *MNRAS*, **522**, 5204
- Beniamini P., Nava L., Piran T., 2016, *MNRAS*, **461**, 51
- Berger E., 2014, *ARA&A*, **52**, 43
- Bertin E., 2006, in Gabriel C., Arviset C., Ponz D., Enrique S., eds, *Astronomical Society of the Pacific Conference Series Vol. 351, Astronomical Data Analysis Software and Systems XV*. p. 12
- Bertin E., 2010, *SWarp: Resampling and Co-adding FITS Images Together*, *Astrophysics Source Code Library*, record ascl:1010.068 ([ascl:1010.068](https://ascl.net/1010.068))
- Bertin E., Arnouts S., 1996, *A&AS*, **117**, 393
- Blandford R. D., McKee C. F., 1976, *Physics of Fluids*, **19**, 1130
- Blandford R. D., Payne D. G., 1982, *MNRAS*, **199**, 883
- Blandford R. D., Znajek R. L., 1977, *MNRAS*, **179**, 433
- Bloom J. S., Kulkarni S. R., Djorgovski S. G., 2002, *AJ*, **123**, 1111
- Bromberg O., Tchekhovskoy A., 2016, *MNRAS*, **456**, 1739
- Brown G. E., Lee C. H., Wijers R. A. M. J., Lee H. K., Israelian G., Bethe H. A., 2000, *New Astron.*, **5**, 191
- CASA Team et al., 2022, *PASP*, **134**, 114501
- Cano Z., Wang S.-Q., Dai Z.-G., Wu X.-F., 2017, *Advances in Astronomy*, **2017**, 8929054
- Caputo R., Gronwall C., Gupta R., Page K. L., Palmer D. M., Parsotan T. M., Siegel M. H., Neil Gehrels Swift Observatory Team 2025, GRB Coordinates Network, **39396**, 1
- Chevalier R. A., Li Z.-Y., 2000, *ApJ*, **536**, 195
- Chiang J., Dermer C. D., 1999, *ApJ*, **512**, 699
- Clocchiatti A., Suntzeff N. B., Covarrubias R., Candia P., 2011, *AJ*, **141**, 163
- Cotter L., Malesani D. B., Palmerio J., de Ugarte Postigo A., Martin-Carrillo A., 2025, GRB Coordinates Network, **39413**, 1
- Dai Z. G., Lu T., 1998a, *Phys. Rev. Lett.*, **81**, 4301
- Dai Z. G., Lu T., 1998b, *A&A*, **333**, L87
- Dainotti M. G., et al., 2024, *MNRAS*, **533**, 4023
- Dey A., et al., 2019, *AJ*, **157**, 168
- Eichler D., Waxman E., 2005, *ApJ*, **627**, 861
- Evans P. A., et al., 2009, *MNRAS*, **397**, 1177
- Fan Y.-Z., Xu D., 2006, *MNRAS*, **372**, L19
- Fong W., Berger E., 2013, *ApJ*, **776**, L8
- Fong W., Berger E., Margutti R., Zauderer B. A., 2015, *ApJ*, **815**, 102
- Fong W.-f., et al., 2022, *ApJ*, **940**, 56
- Frederiks D., Lysenko A., Ridnaya A., Svinkin D., Tsvetkova A., Ulanov M., Cline T., Konus-Wind Team 2025, GRB Coordinates Network, **39423**, 1
- Galama T. J., et al., 1998, *Nature*, **395**, 670
- Galama T. J., et al., 1999, *A&AS*, **138**, 465
- Gendre B., 2025, *Galaxies*, **13**, 7
- Ghosh A., Razzaque S., Moskvitin A., Sotnikova Y., Dukiya N., Gupta R., 2025, GRB Coordinates Network, **39425**, 1
- Gill R., Granot J., 2018, *MNRAS*, **478**, 4128
- Gill R., Granot J., 2023, *MNRAS*, **524**, L78
- Gill R., Nathanail A., Rezzolla L., 2019, *ApJ*, **876**, 139
- Globus N., Levinson A., 2014, *ApJ*, **796**, 26
- Goodman J., 1986, *ApJ*, **308**, L47
- Granot J., Sari R., 2002, *ApJ*, **568**, 820
- Granot J., Piran T., Sari R., 1999, *ApJ*, **513**, 679
- Granot J., Nakar E., Piran T., 2003, *Nature*, **426**, 138
- Greiner J., et al., 2015, *Nature*, **523**, 189
- Gulati A., Anderson G. E., Morley C., Chastain S., Leung J. K., van der Horst A. J., Rhodes L., ATCA PanRadio GRB Collaboration 2025, GRB Coordinates Network, **39501**, 1
- Guo H., et al., 2025, GRB Coordinates Network, **39412**, 1
- Hascoët R., Daigne F., Mochkovitch R., 2012, *A&A*, **541**, A88
- Hjorth J., Bloom J. S., 2012, in Kouveliotou C., Wijers R. A. M. J., Woosley S., eds, , Chapter 9 in "Gamma-Ray Bursts. pp 169–190, [doi:10.48550/arXiv.1104.2274](https://doi.org/10.48550/arXiv.1104.2274)
- Hjorth J., et al., 2003, *Nature*, **423**, 847
- Hu L., Wang L., Chen X., Yang J., 2022, *ApJ*, **936**, 157
- Huang Y. F., Dai Z. G., Lu T., 1999, *MNRAS*, **309**, 513
- Iskandar A., Zhu H. C., Wang X. F., Wang L. T., Yan S., 2025, GRB Coordinates Network, **39446**, 1
- Kann D. A., et al., 2010, *ApJ*, **720**, 1513
- Kashikawa N., et al., 2004, *PASJ*, **56**, 1011
- Kennicutt Jr. R. C., 1998, *ARA&A*, **36**, 189
- Kobayashi S., 2000, *ApJ*, **545**, 807
- Kobayashi S., Sari R., 2000, *ApJ*, **542**, 819
- Kobayashi S., Zhang B., 2003, *ApJ*, **582**, L75
- Kouveliotou C., Meegan C. A., Fishman G. J., Bhat N. P., Briggs M. S., Koshut T. M., Paciesas W. S., Pendleton G. N., 1993, *ApJ*, **413**, L101
- Kumar P., Piran T., 2000, *ApJ*, **532**, 286
- Kumar P., Zhang B., 2015, *Phys. Rep.*, **561**, 1
- Lamb G. P., et al., 2019, *ApJ*, **883**, 48
- Langarica R., et al., 2024, in Bryant J. J., Motohara K., Vernet J. R. D., eds, *Society of Photo-Optical Instrumentation Engineers (SPIE) Confer-*

- ence Series Vol. 13096, Ground-based and Airborne Instrumentation for Astronomy X. p. 130963D, [doi:10.1117/12.3020545](https://doi.org/10.1117/12.3020545)
- Laskar T., Berger E., Margutti R., Perley D., Zauderer B. A., Sari R., Fong W.-f., 2015, *ApJ*, **814**, 1
- Laskar T., et al., 2018, *ApJ*, **859**, 134
- Lattimer J. M., Schramm D. N., 1974, *ApJ*, **192**, L145
- Lazzati D., Rossi E., Covino S., Ghisellini G., Malesani D., 2002, *A&A*, **396**, L5
- Lee W. H., Ramirez-Ruiz E., 2007, *New Journal of Physics*, **9**, 17
- Levan A. J., et al., 2024, *Nature*, **626**, 737
- Li L., et al., 2012, *ApJ*, **758**, 27
- Lien A., et al., 2016, *ApJ*, **829**, 7
- Loeb A., Perna R., 1998, *ApJ*, **495**, 597
- MacFadyen A. I., Woosley S. E., 1999a, *ApJ*, **524**, 262
- MacFadyen A. I., Woosley S. E., 1999b, *ApJ*, **524**, 262
- Magnier E. A., et al., 2020, *ApJS*, **251**, 6
- McCracken H. J., et al., 2003, *A&A*, **410**, 17
- Melandri A., Brivio R., Ferro M., D’Avanzo P., Covino S., Fugazza D., REM Team 2025, GRB Coordinates Network, **39406**, 1
- Meszáros P., Rees M. J., 1993, *ApJ*, **405**, 278
- Mészáros P., Rees M. J., 1997, *ApJ*, **476**, 232
- Metcalf N., Shanks T., Campos A., McCracken H. J., Fong R., 2001, *MNRAS*, **323**, 795
- Metzger B. D., Berger E., 2012, *ApJ*, **746**, 48
- Metzger B. D., et al., 2010, *MNRAS*, **406**, 2650
- Metzger B. D., Giannios D., Thompson T. A., Bucciantini N., Quataert E., 2011, *MNRAS*, **413**, 2031
- Mirabal N., Halpern J. P., An D., Thorstensen J. R., Terndrup D. M., 2006, *ApJ*, **643**, L99
- Modigliani A., et al., 2010, in Silva D. R., Peck A. B., Soifer B. T., eds, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 7737, Observatory Operations: Strategies, Processes, and Systems III. p. 773728, [doi:10.1117/12.857211](https://doi.org/10.1117/12.857211)
- Moharana R., Piran T., 2017, *MNRAS*, **472**, L55
- Moreno Méndez E., Fraija N., Patricelli B., 2015, *New Astron.*, **41**, 53
- Moss M. J., Mochkovitch R., Daigne F., Beniamini P., Guiricé S., 2023, *MNRAS*, **525**, 5224
- Muenter H., et al., 2025, GRB Coordinates Network, **39417**, 1
- Nakar E., Granot J., 2007, *MNRAS*, **380**, 1744
- Nakar E., Piran T., Granot J., 2003, *New Astron.*, **8**, 495
- Nardini M., et al., 2011, *A&A*, **531**, A39
- Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014, HEASoft: Unified Release of FTOOLS and XANADU, Astrophysics Source Code Library, record ascl:1408.004
- Nugent A. E., et al., 2022, *ApJ*, **940**, 57
- O’Connor B., Beniamini P., Kouveliotou C., 2020, *MNRAS*, **495**, 4782
- O’Connor B., et al., 2022, *MNRAS*, **515**, 4890
- Odeh M., Alshamsi S., Manal Pattani N., Guessoum N., 2025, GRB Coordinates Network, **39410**, 1
- Osterbrock D. E., Ferland G. J., 2006, Astrophysics of gaseous nebulae and active galactic nuclei
- Paczynski B., 1986, *ApJ*, **308**, L43
- Paczynski B., 1991, in Gamma-ray Bursts. AIP, pp 144–148, [doi:10.1063/1.42815](https://doi.org/10.1063/1.42815)
- Palmer D. M., et al., 2025, GRB Coordinates Network, **39471**, 1
- Palmerio J. T., Saccardi A., Rayson B., Malesani D. B., Levan A. J., Tanvir N. R., Stargate Collaboration 2025, GRB Coordinates Network, **39418**, 1
- Pankov N., Kim V., Krugov M., Aimuratov Y., Volnova A., Pozanenko A., IKI-GRB-FuN Collaboration 2025a, GRB Coordinates Network, **39422**, 1
- Pankov N., Pozanenko A., Klunlo E., Volnova A., IKI-GRB-FuN Collaboration 2025b, GRB Coordinates Network, **39424**, 1
- Penrose R., Floyd R. M., 1971, *Nature Physical Science*, **229**, 177
- Pereyra M., et al., 2022, *MNRAS*, **511**, 6205
- Perley D. A., Niino Y., Tanvir N. R., Vergani S. D., Fynbo J. P. U., 2016, *Space Sci. Rev.*, **202**, 111
- Perley D. A., et al., 2019, *MNRAS*, **484**, 1031
- Perley D. A., et al., 2021, *MNRAS*, **508**, 5138
- Petropoulou M., Beniamini P., Vasilopoulos G., Giannios D., Barniol Duran R., 2020, *MNRAS*, **496**, 2910
- Pian E., Mazzali P. A., 2006, *Chinese Journal of Astronomy and Astrophysics Supplement*, **6**, 335
- Piran T., 1999, *Phys. Rep.*, **314**, 575
- Planck Collaboration et al., 2020, *A&A*, **641**, A1
- Prochaska J. X., Chen H.-W., Bloom J. S., 2007, *ApJ*, **648**, 95
- Rastinejad J. C., et al., 2022, *Nature*, **612**, 223
- Rees M. J., Meszaros P., 1992, *MNRAS*, **258**, 41
- Rees M. J., Mészáros P., 1998, *ApJ*, **496**, L1
- Ricci R., Troja E., 2025, GRB Coordinates Network, **39433**, 1
- Rowlinson A., O’Brien P. T., Metzger B. D., Tanvir N. R., Levan A. J., 2013, *MNRAS*, **430**, 1061
- Salpeter E. E., 1955, *ApJ*, **121**, 161
- Sari R., 1997, *ApJ*, **489**, L37
- Sari R., Mészáros P., 2000, *ApJ*, **535**, L33
- Sari R., Piran T., 1995, *ApJ*, **455**, L143
- Sari R., Piran T., Narayan R., 1998, *ApJ*, **497**, L17
- Savaglio S., Glazebrook K., Le Borgne D., 2009, *ApJ*, **691**, 182
- Schlegel D. J., Finkbeiner D. P., Davis M., 1998, *ApJ*, **500**, 525
- Schroeder G., et al., 2024, *ApJ*, **970**, 139
- Schroeder G., et al., 2025, *ApJ*, **982**, 42
- Selsing J., Malesani D. B., Goldoni P., et al. 2018, *A&A*, **616**, A48
- Shemi A., Piran T., 1990, *ApJ*, **365**, L55
- Soderberg A. M., et al., 2006, *ApJ*, **650**, 261
- Tam P., Pun C., Huang Y., Cheng K., 2005, *New Astronomy*, **10**, 535
- Troja E., et al., 2007, *ApJ*, **665**, 599
- Troja E., et al., 2022, *Nature*, **612**, 228
- Tsvetkova A., et al., 2017, *ApJ*, **850**, 161
- Vlasis A., van Eerten H. J., Meliani Z., Keppens R., 2011, *MNRAS*, **415**, 279
- Vreeswijk P. M., Ledoux C., Raassen A. J. J., et al. 2013, *A&A*, **549**, A22
- Watson A. M., et al., 2025, GRB Coordinates Network, **39397**, 1
- Woosley S. E., 1993, *ApJ*, **405**, 273
- Yadav M., et al., 2025, *arXiv e-prints*, p. arXiv:2505.08781
- Yang J., et al., 2022, *Nature*, **612**, 232
- Yang Y.-H., et al., 2024, *Nature*, **626**, 742
- Zalamea I., Beloborodov A. M., 2011, *MNRAS*, **410**, 2302
- Zhang B., Mészáros P., 2001, *ApJ*, **552**, L35
- Zhang B., Mészáros P., 2002, *ApJ*, **566**, 712
- Zhang B., Mészáros P., 2004, *International Journal of Modern Physics A*, **19**, 2385
- de Ugarte Postigo A., et al., 2005, *A&A*, **443**, 841
- de Ugarte Postigo A., et al., 2007, *A&A*, **462**, L57
- de Ugarte Postigo A., Thöne C. C., Rowlinson A., et al. 2014, *A&A*, **563**, A62
- de Wet S., et al., 2023, *A&A*, **671**, A116
- de Wet S., et al., 2024, *ApJ*, **974**, 279
- van Eerten H. J., Meliani Z., Wijers R. A. M. J., Keppens R., 2009, *MNRAS*, **398**, L63

APPENDIX A: REFRESHED SHOCK FROM TWO SHELL COLLISION

We consider two spherical shells, where the first ejected shell has initial bulk-LF $\Gamma_{0,3}$ and the second has $\Gamma_{0,6}$; the shells here are labelled according to Figure A1. The two shells travel the same radial distance R_{coll} from the central engine, where the collision occurs at the lab-frame time t_{coll} . The lab-frame time to reach a given radius R is determined by the shell velocity, $\beta(R) = \sqrt{1 - \Gamma^{-2}(R)}$. Here we approximate the radial evolution of the bulk-LF of the first shell as a broken power-law, with $\Gamma_3 = \Gamma_{0,3}$ for $R < R_{\text{dec}}$, when the shell has not reached the deceleration radius, and $(\Gamma_3/\Gamma_{0,3})^2 = \hat{R}^{-m}$ for $R > R_{\text{dec}}$, where we define $\hat{R} = R/R_{\text{dec}}$ and $m = 3 - k$. The lab-frame time taken by the first shell to arrive at a given radius

$\hat{R} > 1$ is $t = R_{\text{dec}}/\beta_{0,3}c + (R_{\text{dec}}/c) \int_1^{\hat{R}} d\hat{R}/\beta(\hat{R})$, where the first term is the time at which the shell decelerates. The arrival time of photons from different parts of the shell when the shell is at radius R is determined by the equal-arrival-time-surface (EATS) equation, such that $T_z \equiv T/(1+z) = t(R) - (R/c)\mu$, where $t(R)$ is the lab-frame time and $\mu = \cos\theta$ with θ being the angle measured from the line-of-sight (LOS) to the emitting material. The on-axis arrival time of photons, i.e. along the LOS, when $\Gamma^2 \propto R^{-m}$, is given by $T_z = R/2(1+m)\Gamma^2 c$ for $\Gamma \gg 1$. Since the time of the re-brightening in the observer frame, $T_{\text{bright}} \gg T_{\text{dec}}$, it also means that the corresponding collision radius $\hat{R}_{\text{coll}} \gg (1+m)^{1/(1+m)} = \sqrt{2}$ for $m = 3 - k$ using $k = 0$. Therefore, the lab-frame time at which the collision occurs is also much greater than the time at which the shell decelerates, i.e. $t_{\text{coll}} \gg R_{\text{dec}}/\beta_{0,3}c$. In this case, the first shell arrives at R_{coll} at lab-frame time $t_{\text{coll}} = [1 + \hat{R}_{\text{coll}}^m/2(1+m)\Gamma_{0,3}^2]R_{\text{coll}}/c$. The second shell, which does not suffer any deceleration, reaches R_{coll} in a lab-frame time $t_{\text{coll}} = t_{\text{em}} + (1 + 1/2\Gamma_{0,6}^2)R_{\text{coll}}/c$, where t_{em} is the engine quiescent time after which it emits the second shell. By comparing the arrival times of the two shells at $R = R_{\text{coll}}$, we get

$$t_{\text{em}} \approx \left[1 - \frac{(1+m)\Gamma_{0,3}^2}{\Gamma_{0,6}^2} \right] T_{\text{bright}}, \quad (\text{A1})$$

which further yields

$$\left(\frac{\Gamma_{0,3}}{\Gamma_{0,6}} \right)^2 = \left[1 - (1+z) \frac{t_{\text{em}}}{T_{\text{bright}}} \right] \frac{[(1+m)\hat{T}_{\text{bright}}]^{1+m}}{(1+m)}, \quad (\text{A2})$$

where $\hat{T}_{\text{bright}} = T_{\text{bright}}/T_{\text{dec}}$. In general, if $t_{\text{em}} \ll T_{\text{bright}}/(1+z)$ then it fixes the ratio of the bulk LFs of the two shells,

$$\left(\frac{\Gamma_{0,3}}{\Gamma_{0,6}} \right)^2 = \frac{[(1+m)\hat{T}_{\text{bright}}]^{1+m}}{(1+m)}. \quad (\text{A3})$$

Since $t_{\text{em}}/T_{\text{bright}} < T_{90}/T_{\text{bright}} \ll 1$ is guaranteed in a binary merger scenario, it forces $\Gamma_3/\Gamma_{0,6} \approx (1+m)^{-1/2} = 1/2$ for $m = 3$ (Kumar & Piran 2000). This also implies that the delay between the emission time of the shells can be approximated as negligible, with $t_{\text{em}} \approx 0$. The arrival time of radiation from the collision radius is given by $\hat{T}_{\text{bright}} = \hat{R}_{\text{coll}}^{1+m}/(1+m)$ when $\Gamma_3 \gg 1$, where

$$\hat{R}_{\text{coll}} \equiv \frac{R_{\text{coll}}}{R_{\text{dec}}} = \left[(1+m) \left(\frac{\Gamma_{0,3}}{\Gamma_{0,6}} \right)^2 \right]^{1/m}. \quad (\text{A4})$$

In this case it is required that $\Gamma_{0,6} < \Gamma_{0,3}$ for $\hat{R}_{\text{coll}} > 1$.

The relative LF between the two shells at the time of collision is $\Gamma_{\text{rel}} \approx (\Gamma_3/\Gamma_{0,6} + \Gamma_{0,6}/\Gamma_3)/2 = 5/4$ for $\Gamma_3, \Gamma_{0,6} \gg 1$. In order to produce a strong shock, Γ_{rel} must significantly exceed the LF corresponding to the local sound speed (c_s) in the first shell. Since the collision occurs after the passage of the reverse shock in the first shell, due to its interaction with the external medium, it can be assumed to be relativistically hot. In that case, the sound speed is $\beta_s = c_s/c = 1/\sqrt{3}$, with the corresponding LF $\Gamma_s = \sqrt{3}/2 \approx 1.22 \leq \Gamma_{\text{rel}}$.

Next, we calculate the emission that arises from the two shell collision and which produces the re-brightening. As the two shells collide, a forward shock is launched into the first shell and a reverse shock into the second shell. In total, there are six different regions with different dynamical evolution as illustrated in Figure A1 (Zhang & Mészáros 2002): (1) unshocked ISM, (2) ISM shocked by the forward shock from the first shell, (3) material from the first shell shocked by the early passage ($T_{x1} \lesssim T_{\text{dec}}$) of the reverse shock, (4) relativistically hot material in the first shell now shocked by the forward shock from the second shell, (5) material of the second

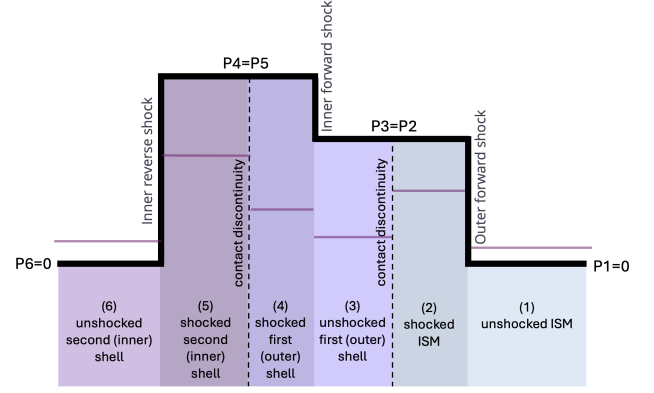


Figure A1. Sketch (not to scale) of the different shocked and unshocked regions that arise in the collision of two kinetic-energy-dominated shells. The thick solid line indicates the pressure, or the internal energy density, in each region. The thin solid line indicates the comoving mass density. Figure adapted from Zhang & Mészáros (2002).

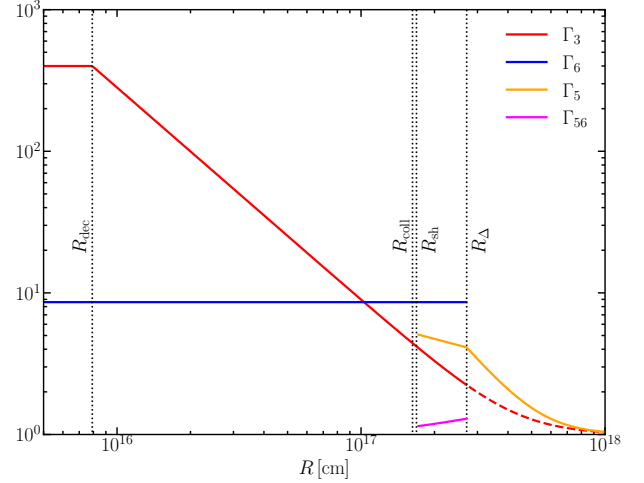


Figure A2. Shell dynamics with $E_{k,\text{iso},6}/E_{k,\text{iso},3} = 24$ and $\Gamma_{0,3}/\Gamma_{0,6} = 46.5$. All other parameters are the same as the best-fit parameters shown in the legend of Figure 8. Different important radii are also shown, where the first shell decelerates at R_{dec} and the second shell catches up from behind and merges with the first at R_{coll} . Two shocks, in addition to the external forward shock by the first shell, form at R_{sh} , from which a reverse shock crosses the second shell at R_{Δ} . The dynamics of the first decelerating shell are altered (dashed line) at $R > R_{\Delta}$ due to injection of energy by the second shell.

shell now shocked by the reverse shock from the collision, and (6) unshocked material of the second shell. All physical quantities in what follows refer to these regions with the corresponding number. To relate the properties of the upstream flow with that of the downstream across the three shocks, we use the shock jump conditions. For a strong shock going into a cold medium, i.e. $\rho_u c^2 \gg e_u + P_u$, where ρ_u , e_u , and P_u are the proper mass density, internal energy density, and pressure of the upstream medium (with subscript ‘u’), the shock-jump conditions yield (Blandford & McKee 1976)

$$\frac{e_d}{n_d} = (\Gamma_{ud} - 1)m_p c^2, \quad \frac{n_d}{n_u} = \frac{\hat{\gamma}\Gamma_{ud} + 1}{\hat{\gamma} - 1} = 4\Gamma_{ud}, \quad \hat{\gamma} = \frac{4\Gamma_{ud} + 1}{3\Gamma_{ud}}$$

(A5)

where Γ_{ud} is the relative LF between the upstream and downstream (with subscript 'd') media and $\hat{\gamma}$ is the adiabatic index of the downstream medium with $\hat{\gamma} = 4/3$ (5/3) for a relativistic (non-relativistic) fluid. The above shock-jump condition applies to the forward shock between regions (1) and (2) and the reverse shock between regions (5) and (6). The shock between regions (3) and (4) is propagating into a relativistically hot region, i.e. $e_u + P_u \gg \rho_u c^2$ and $P_u = (\hat{\gamma} - 1)e_u = e_u/3$ for $\hat{\gamma} = 4/3$. Therefore, it admits different shock-jump conditions (Kumar & Piran 2000; Zhang & Mészáros 2002)

$$\Gamma_{ud}^2 = \frac{(3e_d + e_u)(e_d + 3e_u)}{16e_d e_u}, \quad \left(\frac{n_d}{n_u}\right)^2 = \frac{(3e_d + e_u)}{e_d + 3e_u} \frac{e_d}{e_u}. \quad (\text{A6})$$

Since the emission from the reverse shock makes the dominant contribution to the total flux until the shock crosses the second shell, we first derive the flux scaling relations for that. When the collision occurs and the second shell decelerates, it is important to know if the reverse shock is propagating into a radially expanding shell (thin shell regime) or that with a fixed radial width (thick shell regime; Sari & Piran 1995). If the initial radial width of the second shell is $\Delta_{0,6} = c\delta T/(1+z)$, where δT is the activity time of the central engine, the shell starts to spread at the radius $R_s = \Delta'_{0,6}\Gamma_{0,6} = \Delta_{0,6}\Gamma_{0,6}^2$. For the shell to be thick at the time of collision, i.e. $\hat{R}_s > \hat{R}_{\text{coll}}$, its initial LF must exceed that of the first shell,

$$\frac{\Gamma_{0,6}}{\Gamma_{0,3}} > \sqrt{\frac{2T_{\text{dec}}}{\delta T}} [(1+m)\hat{T}_{\text{bright}}]^{\frac{1}{2(1+m)}} \approx 16.8 T_{\text{bright},5}^{1/8} T_{\text{dec},1}^{3/8} \delta T^{-1/2}, \quad (\text{A7})$$

which contradicts the earlier condition of $\Gamma_{0,2} < \Gamma_{0,1}$. Therefore, the second shell must start to spread before the collision, in which case the comoving number density of the shell is $n_6 = M_6\Gamma_{0,6}/4\pi R^3 m_p \propto R^{-3}$, where $M_6 = E_{k,\text{iso},6}/\Gamma_{0,6}c^2$ is the shell mass and $E_{k,\text{iso},6}$ is its kinetic energy.

From the shock-jump condition in Equation (A5), we find $n_5 = 4\Gamma_{56}n_6$ and $e_5 = 4(\Gamma_{56}-1)\Gamma_{56}n_6 m_p c^2$. Regions 4 and 5 are separated by a contact discontinuity, where the shocked fluids in the two regions are in pressure equilibrium, i.e. $P_5 = P_4$, and also move with the same velocity, i.e. $\Gamma_5 = \Gamma_4$, which implies that $\Gamma_{56} = \Gamma_{46}$. In order to calculate Γ_{56} we need to know Γ_4 , where the latter is obtained from the shock-jump condition in Equation (A6) that yields, $\Gamma_{43}^2 = (3e_4/e_3 + 1)(e_4/e_3 + 3)/16(e_4/e_3)$. Here, $e_4 = e_5$ due to both being relativistically hot and in pressure equilibrium. We assume that region 3 is still relativistically hot after RS passage, so that $P_3 \approx P_2$ and $e_3 \approx e_2$, and also $\Gamma_3 \approx \Gamma_2$. In that case, the jump condition in Equation (A5) yields $e_4/e_3 \approx e_5/e_2 \approx (\Gamma_{56}-1)\Gamma_{56}n_6/\Gamma_2^2 n_1$.

We solve the coupled dynamics of the different regions and show the LFs of the relevant regions in the left column of Figure A2 for the two different solutions obtained from the light curve fits in Figure 8. Even though the two shells make contact at the radius R_{coll} , the shocks do not form until the shells reach $R_{\text{shock}} \geq R_{\text{coll}}$ when the condition that $e_4 > e_3$ is met. At $R > R_{\text{shock}}$, the RS starts to propagate into the inner shell and extracts its kinetic energy. The differential number of baryons entering the shock can be calculated as $dN_6 = 4\pi R^2 n_6 \Gamma_6 d\Delta_5$, where $d\Delta_5 = (\beta_6 - \beta_5)(1 - \Gamma_6 n_6/\Gamma_5 n_5)^{-1} dR$ is the infinitesimal width of the shocked region, as obtained from baryon number conservation. The total mass shocked by the RS is then $M_5 = \int_{R_{\text{shock}}}^{R_\Delta} m_p dN_6$, where R_Δ is the shock crossing radius, and it is obtained when $M_5 = M_6$. In the cases shown in Figure A2, the RS moves through the inner shell at a non-relativistic speed, with

$\Gamma_{\text{RS}} \sim \Gamma_{56}$, and crosses the shell over $\Delta R/R_{\text{cross}} \lesssim 1.5 - 2$. After RS passage, it is expected that the LF of the now entirely shocked inner shell follows $\Gamma_5 \propto R^{-g}$, where $3/2 \leq g \leq 7/2$ (Kobayashi & Sari 2000) and we assume $g = 2$. Due to energy injection by the inner shell, the dynamics of the merged two-shell system are altered, which requires more careful modelling and are not considered here.

APPENDIX B: CENTRAL ENGINE

In order to produce a GRB we need a central engine, whether the event is coming from a compact-objects merger, i.e., a low mass BH-NS, or a NS-NS (Lattimer & Schramm 1974; Metzger et al. 2011), or from a Collapsar as was explained in Section 1 (Woosley 1993). So far, neither our restricted observations nor our analytical models can tell which one is responsible for GRB 250221A.

We know from our analysis (see Section 5.4) that the central engine must deliver not less than $E_k > 6.3 \times 10^{51} (\theta_j/0.25)^2$ erg for a GRB in G2; but this makes the dubious assumption that efficiencies within the process are close to one, casting aside the equipartition theorem. Hence, we look for more robust engines which can deliver several tens of times these energies.

The most accepted and well studied central engines (CE) can be summarized as follows:

(i) $\nu\bar{\nu}$ annihilation from accretion onto a NS or BH (see, e.g. MacFadyen & Woosley 1999b; Zalamea & Beloborodov 2011; Globus & Levinson 2014): When the mass-accretion rate close to the compact object (CO: BH or NS) is larger than a few hundredths of solar masses per second and the spin (of the CO) is large; or accretion rates around a few tenths of a solar mass per second and the spin is low; conditions are optimal for nuclear burning in the inner disk and, thus, production of large amounts of $\nu\bar{\nu}$. Zalamea & Beloborodov (2011) have shown that powers $\dot{E}_{\nu\bar{\nu}} \gtrsim 10^{52}$ erg s $^{-1}$ can be reached for accretion rates $\gtrsim 1 M_\odot$ s $^{-1}$, and cannot exceed $\sim 5 \times 10^{52}$ erg s $^{-1}$.

(ii) Millisecond magnetar spinning down (Metzger et al. 2011): Utilizing a large dipolar magnetic field to extract the rotational kinetic energy stored in a ms magnetar. If the field is of order $B \approx 10^{15}$ G, the spin downtime is of order of seconds, and the energy is around $E_{\text{rot}} = \frac{I\Omega^2}{2} \lesssim 10^{53}$ erg for a 3- $M_\odot$, ms-spin, NS (although unstable, and above the TOV limit, such a large mass may be expected to briefly survive after a NS-NS merger, or after accreting during a core collapse event, when centrifugal force helps to achieve hydrostatic equilibrium).

(iii) A Kerr BH with Blandford-Znajek engine (Blandford & Znajek 1977; Brown et al. 2000): A Penrose process (Penrose & Floyd 1971) where a Kerr BH, with an attached magnetic field finds itself surrounded by a plasma-built accretion disk, works as an electric generator and the average of the Poynting vector points in the direction of the rotational axis, delivering thus, a fraction of the Kerr's BH rotational kinetic energy into jets. Typical Blandford-Znajek (BZ) luminosities (L_{BZ}) are of order $L_{\text{BZ}} \approx 10^{52} a_\star^2 \frac{\Omega(\omega_{\text{BH}} - \Omega)}{\omega_{\text{BH}}^2} \left(\frac{M_{\text{BH}}}{5M_\odot}\right)^2 \left\langle \frac{B}{10^{15}\text{G}} \right\rangle^2$ erg s $^{-1}$, where $a_\star$ is the dimensionless Kerr (or spin) parameter of the BH, ω_{BH} is the angular velocity of the BH, and Ω is the angular velocity of the accretion disk.

(iv) Schwarzschild BH or Kerr BH with BP engine (Blandford & Payne 1982): Again, an electric-generator like process, but not a Penrose process. This is magneto-rotational process that extracts rotational energy from the accretion disk.

A two-peaked afterglow may be explained by the collision of two shells at a radius of $R_{\text{coll}} \simeq 10^{17}$ cm. The simplest model assumes they both move with similar initial Lorentz factors, but are launched about two seconds apart from each other. The first shell sweeps the ISM away, gradually slowing down as it accumulates material on its head. The second shell, having a clear path, maintains a constant speed until it finally catches up with the first one, producing the rebrightening we observe.

Producing two peaks, instead of one, or three, allows for placing constraints on the nature of the central engine. A single-episode engine can be produced by both (CO merger or a Collapsar) and they may use any one of the four central engines (or a combination of them) described above. Instead, a three peaked process may involve, as pointed out in [Moreno Méndez et al. \(2015\)](#) for GRB 110709B, an initial CE powered by a ms magnetar that powers the first peak; the magnetar collapses onto a BH as it loses its centrifugal support due to the powering of the jet. The collapse releases the binding energy of the BH, sending the blast wave down the jet-produced funnels as they get collimated (this allowed for the prediction and discovery of the intermediate peak in GRB 110709B in that work). Finally, after substantial mass and angular momentum accretion, the BH turns from a Schwarzschild into a Kerr BH; this, along with the surrounding disk, allows for the turning on of a BZ central engine which powers the third and last peak. If only two peaks are produced, this implies that the conditions for the third, BZ, engine were not fulfilled. This is most easily explained if the CE is not produced by a Collapsar but, instead, by a NS-NS merger with a $B \gtrsim 10^{15}$ G field which produces a centrifugally-supported massive, ms magnetar powering up a two-second GRB; as it slows down, it collapses onto a Schwarzschild BH, releasing a blast wave with energy $E_B \simeq \mathcal{G}^3 \left(\frac{M_{\text{BH}}^2}{R_{\text{BH}}} - \frac{M_{\text{NS}}^2}{R_{\text{NS}}} \right) \lesssim (20 - 15) \cdot 10^{53} \text{erg}$, which gets collimated by the infalling, accreting, material. The infall, nonetheless, is too small to spin the BH up and power up a BZ engine.

Although other mechanisms exist to switch on and off a CE engine (e.g., interrupted accretion stages), allowing for the timing and strong energy differences is simple using the aforementioned mechanism. Two peaks in the emission coming from two colliding shells allow putting constraints on the nature of CE and type of event (Collapsar vs merger), favouring, thus, a SGRB from a NS-NS merger for GRB 250221A. However, if a single shell (with energy injection, density gradient, or other mechanism resulting from different accretion stages) is the preferred model for producing the rebrightening, then no constraints can be placed on either of them.

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.