The long-active afterglow of GRB 210204A: Detection of the most delayed flares in a Gamma-Ray Burst

Harsh Kumar,1,2* Rahul Gupta,3,4† Divita Saraogi,1 Tomás Ahumada,5 Igor Andreoni,6 G.C. Anupama,7 Amar Aryan,3,4 Sudhanshu Barway,7 Varun Bhalerao,1 Poonam Chandra,8 Michael W. Coughlin,9 Dimple3,4, Anirban Dutta7, Ankur ghosh3, Anna Y. Q. Ho10,11, E. C. Kool,11, Amit Kumar3,13, Michael S. Medford14,15, Kuntal Misra3, Shashi B. Pandey3, Daniel A. Perley17, Reed Riddle19, Amit Kumar Ror3, Jason M. Setiadi18, Yuhan Yao19
1Physics Department, Indian Institute of Technology Bombay, Powai, 400 076, India
2LSTC DSFP Fellow-2018
3Aryabhata Research Institute of Observational Sciences, Manora Peak, Nainital - 263 001, India
4Department of Physics, Deen Dayal Upadhyaya Gorakhpur University, Gorakhpur 273009, India
5Department of Astronomy, University of Maryland, College Park, MD 20742, USA
6Joint Space Science Institute: College Park, Maryland, US
7Indian Institute of Astrophysics, 2nd Block 100 Feet Rd, Koramangala Bangalore, 560 034, India
8Swarna Jayanti Fellow, Department of Science & Technology, India, National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Ganeshkhind, Pune 411007, India
9School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA
10Department of Astronomy, University of California, Berkeley, 94720, USA
11Miller Institute for Basic Research in Science, 468 Donner Lab, Berkeley, CA 94720, USA
12The Oskar Klein Centre, Department of Astronomy, Stockholm University, AlbaNova, SE-10691, Stockholm, Sweden
13School of Studies in Physics and Astrophysics, Pandit Ravishankar Shukla University, Raipur, Chhattisgarh-492010, India
14Department of Astronomy, University of California, Berkeley, 94720
15Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720
16Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, UK
17University of Minnesota, School of Statistics, 313 Ford Hall, 224 Church Street SE, Minneapolis, MN 55455, USA
18Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA

ABSTRACT
We present results from extensive broadband follow-up of GRB 210204A over the period of thirty days. We detect optical flares in the afterglow at 7.6 × 10^5 s and 1.1 × 10^6 s after the burst: the most delayed flaring ever detected in a GRB afterglow. At the source redshift of 0.876, the rest-frame delay is 5.8 × 10^5 s (6.71 d). We investigate possible causes for this flaring and conclude that the most likely cause is a refreshed shock in the jet. The prompt emission of the GRB is within the range of typical long bursts: it shows three disjoint emission episodes, which all follow the typical GRB correlations. This suggests that GRB 210204A might not have any special properties that caused late-time flaring, and the lack of such detections for other afterglows might be resulting from the paucity of late-time observations. Systematic late-time follow-up of a larger sample of GRBs can shed more light on such afterglow behaviour. Further analysis of the GRB 210204A shows that the late time bump in the light curve is highly unlikely due to underlying SNe at redshift (z) = 0.876 and is more likely due to the late time flaring activity. The cause of this variability is not clearly quantifiable due to the lack of multi-band data at late time constraints by bad weather conditions. The flare of GRB 210204A is the latest flare detected to date.

Key words: gamma-ray burst: general, gamma-ray burst: individual: GRB 210204A, methods: data analysis

1 INTRODUCTION
Long Gamma-Ray Bursts (GRBs) originate from the core collapse of massive stars (Kouveliotou et al. 1993; Kumar & Zhang 2015). The GRB emission consists of two distinct phases: the prompt emission typically observed in soft γ-rays and hard X-rays, and the afterglow, which has been detected across a wide range of wavelengths from radio to TeV band (Piran 2004; MAGIC Collaboration et al. 2019).

GRB prompt emission is created by energy dissipation as the relativistic jet accelerates particles via either internal shocks or magnetic reconnection (Pe’er 2015). These particles typically emit a
non-thermal spectrum that is often dominated by synchrotron radiation (Burgess et al. 2020; Zhang 2020). However, the detailed radiation physics of GRBs is not fully understood (Kumar & Zhang 2015). In practice, the prompt GRB spectrum is usually modelled phenomenologically as a “Band” spectrum (Band et al. 1993). In addition, some spectra show additional features such as thermal components or multi-coloured blackbody peaks (Pe’Er & Ryde 2017), inverse Compton scattered components (Derishev et al. 2001), low energy spectral breaks (Oganesyan et al. 2018), deviation from synchrotron spectra (Daigne et al. 2011), etc. The physical/spectral parameters of prompt emission — like the Lorentz factor \( \Gamma \), the peak energy \( E_p \), the isotropic equivalent energy \( E_{\gamma,\text{iso}} \), or the isotropic luminosity \( L_{\gamma,\text{iso}} \) — show some correlations like the Amati correlation (Amati 2006), which have been explored for understanding GRB properties as well as applying them for cosmology.

The interaction of the jet with the ambient medium gives rise to synchrotron emission, commonly known as the afterglow (Mészáros & Rees 1997; Sari et al. 1998; Piran 2005). The afterglow is broadband and lasts much longer than the GRB: being visible for hours to days in X-ray bands, days to weeks in optical, and weeks to months at radio wavelengths. From the first afterglow detection by BeppoSAX (GRB 970228; Costa et al. 1997), the understanding of afterglows has increased tremendously over the decades — with a huge boost from the Neil Gehrels Swift Observatory with its rapid response abilities (Gehrels et al. 2004). The afterglow emission is phenomenologically simple to model, and the flux \( F \) is often fit by a simple power-law in both time and frequency, \( F \propto t^{-\alpha} \nu^{-\beta} \). The temporal decay index \( \alpha \) and spectral decay index \( \beta \) typically follow the \( \alpha-\beta \) closure relation predicted by the forward shock model (Zhang 2021; Piran 2005). Some GRB afterglows show features that provide insights into the physics of the source: for instance, jet breaks (Rhoads 1999; Sari et al. 1999), supernovae in long GRBs (Galama et al. 1998; Galama et al. 1999), and flaring activity generated by various mechanisms (Burrows et al. 2005b; Falcone et al. 2007).

GRB 210204A, first reported by Fermi Gamma-Ray Burst Monitor (GBM), is a long GRB with multiple pulses in the prompt emission (Meegan et al. 2009). The optical afterglow was detected by the ZwickyTransient Facility (ZTF; Bellm 2014) and followed by multiple observatories in many wavebands. Here, we report our findings based on extensive follow-up of the source with multiple telescopes. The paper is organised as follows. In §2, we describe our observations and data reduction. We also list out public data from various sources that we have used in this work. §3 discusses the temporal and spectral characteristics of the prompt emission. In §4 we undertake broadband modelling of the afterglow, showing clear evidence of late-time brightening. We conclude by discussing various causes for this in §5 and identifying the most plausible one.

## 2 Observations and Data Analysis

In this section, we present the prompt and afterglow observations carried out by various space and ground-based telescopes.

### 2.1 Prompt Emission

GRB 210204A was discovered by the Fermi (GBM, Meegan et al. 2009) at UT 2021-02-04 06:29:25 (hereafter, \( T_0 \)). The source was first localised to RA = 109.1°, Dec = 9.7° (J2000) with a statistical uncertainty of 4.0° (Fermi GBM Team 2021). The burst was also detected by Gravitational-wave high-energy Electromagnetic

![Figure 1. Top four panels: Energy-resolved Fermi-GBM prompt emission light curves (back-ground subtracted) of GRB 210204A. The vertical red, blue and green lines indicate the duration of the first, second, and third episodes, respectively. The vertical dashed-dotted line indicates the peak used to calculate the isotropic luminosity of the burst. Bottom two panels: AstroSat-CZTI light curves in 20-200 keV and 100-500 keV energy range for GRB 210204A. The four colours (blue, green, red, and cyan) correspond to data from four quadrants (A, B, C, and D) of the instrument. The GRB is detected more prominently in quadrants A and D due to the location of the GRB on the sky.](https://threeml.readthedocs.io/en/latest/)

**Counterpart All-sky Monitor (GECAM-B, Li et al. 2021), Konus-Wind (Frederiks et al. 2021), and AstroSat (Waratkar et al. 2021).** The source localisation was refined by BALROG (Kunzweiler et al. 2021), and further by the Inter-Planetary Network (IPN) by using data from Fermi, Integral, Swift, Konus-Wind, and Mars-Odyssey-HEND (Hurley et al. 2021).

In this section, we focus on the analysis of data from Fermi and AstroSat (Figure 1).

#### 2.1.1 Fermi-GBM

We retrieved the Fermi-GBM data (the time-tagged event (TTE) mode) of GRB 210204A from the Fermi Science Support Center archives. We performed the temporal and spectral analysis of GBM data using three sodium iodide (NaI) detectors (NaI b, NaI 7, and NaI 9) and one bismuth germanate (BGO) detector (BGO 1). These detectors have following GRB observing angles NaI b: 25° degree, NaI 7: 35° degree, NaI 9: 47°, and BGO1: 25°, respectively. For the temporal analysis of Fermi-GBM data, we utilized RMFIT version 4.3.2 software and generated the prompt emission background subtracted light curve of GRB 210204A in different energy ranges. Furthermore, we performed the spectral analysis of Fermi-GBM data using the Multi-Mission Maximum Likelihood framework (Vianello et al. 2015, 3ML). We performed time-integrated as well as time-resolved spectral analysis of GBM data to constrain the possible emission mechanisms of GRB 210204A. We started the spectral modelling using traditional GRB model called Band or GRB function (Band et al. 1993). In addition to Band function, we explore various

1. [https://fermi.gsfc.nasa.gov/ssc/data/access/]
2. [https://fermi.gsfc.nasa.gov/ssc/data/analysis/rmfit/]
3. [https://threeml.readthedocs.io/en/latest/]
other possible models such as simple power-law model, a power-law model with a high energy spectral cutoff (cutoffpl), Black Body function to search for photospheric signature in the spectrum, a power-law function with two sharp spectral breaks (bkn2pow\(^4\)), or combination of these models. We utilised the deviance information criterion (DIC; Spiegelhalter et al. 2002) to find the best fit model. A more detailed methodology for GBM data analysis is discussed in Gupta et al. (2021b, 2022).

### 2.1.2 AstroSat CZTI

AstroSat Cadmium Zinc Telluride Imager (CZTI; Bhalerao et al. 2017) detected the second and third pulse of GRB 210204A, with a total of 18141 photons: 94% of which came from the brighter third pulse (Waratkar et al. 2021; Sharma et al. 2020). These two pulses were also clearly seen in the veto detectors. In detector coordinates, the GRB was incident from \(\theta = 75.43\) deg and \(\phi = 172.80\) deg: just 15 deg from the detector plane. CZTI can be used to measure the polarisation of GRBs by analysing two-pixel Compton events (Vadawale et al. 2015; Chattopadhyay et al. 2014). However, such measurements are robustly possible only for GRBs with \(\theta < 60\) deg (Chattopadhyay et al. 2019) — ruling out the possibility of polarimetric studies of GRB 210204A.

### 2.2 Multiwavelength Afterglow

The large 4\(^{\circ}\) positional uncertainty in the Fermi localisation precluded prompt follow-up observations by most telescopes. However, Kool et al. (2021) used the wide-field ZTF and reported the discovery of a fast optical transient ZTF21aagwbjr/AT2021buv, a candidate afterglow for GRB 210204A ~ 38 mins after the trigger. Subsequent follow-up observations by multiple telescopes verified the fading nature of this source and confirmed that it was indeed the afterglow of GRB 210204A.

#### 2.2.1 X-ray afterglow

Equipped with the precise afterglow position, the Neil Gehrels Swift Observatory started Target-of-Opportunity observations of the GRB 210204A field about 1.6 \(\times\) 10\(^5\) s after the initial burst (Evans & Swift Team 2021). The Swift X-ray telescope (XRT; Burrows et al. 2005a) detected an uncatalogued X-ray source at RA, Dec = 117.08071 deg, +11.40951 deg (J2000), consistent with the optical position. Multiple observations obtained till 3 \(\times\) 10\(^5\) s after the burst confirmed the fading nature of this source.

We used the XRT online repositories by Evans et al. (2007, 2009) to retrieve the light curves\(^5\) and spectra\(^6\), respectively. We undertook spectral analysis with the X-Ray Spectral Fitting Package (XSPEC; Arnaud 1996) version 12.10.1. The 0.3-10 keV spectra were modelled as a simple absorbed power-law (using the XSPEC phabs model). For the time-averaged XRT spectrum (from \(T_0 + 1.61 \times 10^5\) to \(T_0 + 1.73 \times 10^5\) s), we get \(\Gamma = 1.73^{+0.28}_{-0.26}\) and \(N_H = 6.43^{+5.40}_{-4.19} \times 10^{21}\) cm\(^{-2}\). In Table A3, we give the temporal evolution of XRT unabsorbed fluxes and photon indices (determined from the hardness ratio) obtained from the Swift Burst Analyser web page, supported by the UK Swift Science Data Centre.

\(^4\) https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node140.html

\(^5\) https://www.swift.ac.uk/xrt_curves/

\(^6\) https://www.swift.ac.uk/xrt_spectra/
300 s exposures in the r’ filter, with each exposure having a limiting magnitude of ~ 20.5 mag. We used the 2.0 m Himalayan Chandra Telescope (HCT) on three nights: 2021 February 07, 2021 February 12 and 2021 February 14, under proposal number HCT-2021-C1-P2. Data were obtained in Bessel V, R, and I filters (Table A1). The 3.6 m Devasthal Optical Telescope (DOT), located at the Devasthal Observatory of Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India (Sagar et al. 2019) was triggered under our ToO proposal number HCT-2021-C1-P19 (PI: Ankur Ghosh) for the follow up. We observed GRB 210204A on multiple epochs with the 4K CCD IMAGER (Pandey et al. 2018; Kumar et al. 2021). The first observations were obtained in BVRI filters (Gupta et al. 2021c), while data on subsequent nights were obtained in the SDSS r filter. Further, we also obtained data with the 1.3 m Devasthal Fast Optical Telescope (DFOT) located at Devasthal observatory of ARIES, Nainital, India (Sagar et al. 2011) under our ToO Proposal ID DFOT-2021A-P6 (PI: Rahul Gupta). We obtained data in B, V, R, and I filters on 2021-06-06 (T0 + 2.4 d), and more data in R and I bands on 2021-02-13 UT.

Data obtained from all these facilities were reduced in similar manner using a python based reduction pipeline. Images were calibrated using bias and flat frames; pipeline made use of Astro-SCAPPY (McCully & Tewes 2019) python package to remove cosmic rays from the science images. Once the images were corrected for all artefacts, we solved the images for astrometry using astrometry.net solve-field engine (Lang et al. 2010) in offline mode. Sources in images were extracted in the form of a locally generated catalogue via SExtractor (Bertin & Arnouts 1996). PSFEx astrometric software (Bertin 2011) gave the PSF profile of the sources, which was used to get magnitudes of stars in the images. For images obtained in ugriz filters, these magnitudes were cross-matched with Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) DR1 catalogue (Chambers et al. 2016) and Sloan Digital Sky Survey (SDSS) DR12 catalogue (Alam et al. 2015) using VizieR to get the zero-points of the images. While, for BVRI filter images, we used data from Sloan Digital Sky Survey (SDSS) (Alam et al. 2015) and converted the magnitudes to VRI bands using Lupton (2005) transformations to estimate the zero-points. For later epochs where the afterglow was fainter, multiple exposures were stacked together using SWarp (Bertin et al. 2002). Table A1 lists the magnitudes with 1-sigma uncertainties. In case the source was not detected, we report 5-sigma upper limits.

In addition to the observations taken by our group, we also use publicly available data reported in Gamma-ray Coordination Network (GCN) by various groups. This set includes data from the ZTF published in (Andreoni et al. 2021), 1.6-m AZT-33IK telescope8, 70 cm AS-32 telescope (Molotov et al. 2009), Large Binocular Telescope Hill (2010), 2.6-m Shajn Telescope (Ioannisiani et al. 1976) and the AZT-20 at Assy-Turgen observatory9. These data, along with the GCN references, are tabulated in Table A2.

Figure 2 shows the detection of GRB afterglow with DOT (located by the green circle in the image). In DOT images, a galaxy is present ~ 4.4” away from the afterglow position. This transforms to a physical distance of ~ 33 kpc from GRB location, which is rather large for the galaxy to be the host of GRB 210204A. Further, the photometric redshift of this galaxy is zphot = 0.436 makes it implausible to be the host of GRB 210204A.

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8 http://en.iszf.irk.ru/Sayan_Solar_Observatory
9 https://fai.kz/observatories/assy-turgen
**Spectroscopy:** We triggered a long-slit spectrum of GRB 210204A with GMOS-S under our ToO program GS-2021A-Q-124 (PI: A. Ho). The observation, conducted in the Nod-and-Shuffle mode with a 1′′-wide slit, started at 2021-02-06 01:19:09.2 UT, corresponding to 42.8 hours after the Fermi-GBM trigger. We obtained 2×450 s spectroscopic exposures with the B600 grating and 2×450 s exposures with the R400 grating, providing coverage over the range 3620–9600 Å. Flux calibration was not performed. The spectrum was reduced using the IRAF package for GMOS. We identified a series of strong absorption features at z = 0.876 superposed on a relatively flat, featureless continuum (Figure 3).

We also detected intervening absorption systems of Mg II λλ2796, 2803 at z = 0.666 and z = 0.712. This interpretation is consistent with that of Izzo et al. (2021), who obtained spectra using ESO VLT UT3 equipped with X-shooter spectrograph ~ 1.79 days after the trigger. Their spectra spanned the wavelength range from 3000-21000 Å in which they report a few absorption lines of Al II, Ca II, Fe II, Mg I, Mg II, Zn II, Ca H and K detected at a common redshift of z = 0.876. They also detect three intervening Mg II absorbers at redshifts of z = 0.71, 0.66, and 0.57.

### 2.2.3 Radio afterglow

The GRB 210204A event was triggered with the upgraded Giant Metrewave Radio Telescope (uGMRT) at 2021 Feb 20.56 UT in band 5 (1000–1450 MHz). The observations were two hours in duration, including overheads using a bandwidth of 400 MHz. We use the Common Astronomy Software Applications (CASA; McMullin et al. 2007) for data analysis. The data were analysed in three major steps, i.e. flagging, calibration and imaging using the procedure laid out in Maity & Chandra (2021). A source was clearly detected at the RA(J2000) = 07:48:19.34, Dec(J2000) = 11:24:33.91. This position is consistent with the position reported by ZTF for the GRB (Kool et al. 2021). Further follow-up observations were triggered on 2021 Mar 07.59 UT and 2021 Mar 09.56 UT in the uGMRT band 4 and band 5 respectively, 2 hours at each band including overheads. In both observation the source was detected with a resolution of 2.66′′×1.74′′ and 6.87′′×2.05′′. Table A4 lists the detailed radio followup information.

### 3 PROMPT EMISSION

We analyse the Fermi data of the prompt emission to characterise GRB 210204A and compare it with the overall GRB population.

#### 3.1 Spectral analysis of the complete GRB

The prompt emission light curve of GRB 210204A obtained using Fermi-GBM data shows three distinct episodes, separated by quiescent temporal gaps (see Figure 1). The first two episodes have relatively faint and simple fast rising and exponential decay profiles, but the third and brightest episode has rich sub-structure. The T90 duration for the entire burst is 207.86 ± 0.06 s. The time-integrated (the entire duration of the burst) Fermi-GBM spectrum (from T90-9.73 to T90 +279.55 s) could be best explained using traditional Band plus Blackbody model with following spectral parameters: peak energy (Ep) = 146 ± 14 keV, low energy spectral index αpt = −1.30 ± 0.07, high energy spectral index βpt = −2.39^{+0.17}_{−0.18} and temperature kTBB = 6.5 ± 0.6 keV.

Table 1. Comparison between the characteristics of three episodes of GRB 210204A. The quiescent duration between the first two episodes is ~ 26.2 s, while that between the second and third episode is ~ 116.2 s. A blackbody component is needed only for the third episode (§3.2). All reported values are observer frame values. The total energy and luminosity were calculated using the source redshift z = 0.876. T90: Duration in 50–300 keV band; HR: ratio of the counts in 50 - 300 keV to the counts in 10 - 50 keV; Ep, α, β: Band spectral fit parameters; F: Bolometric energy flux; Eγ,iso: Isotropic energy; Lp,iso: Isotropic peak luminosity.

| Characteristics | Episode 1 | Episode 2 | Episode 3 |
|-----------------|-----------|-----------|-----------|
| T90 (s) in 50 - 300 keV HR | 12.04 ± 0.02 | 12.81 ± 0.04 | 8.26 ± 0.05 |
| Ep (keV) | 36 ± 9 | 197 ± 30 | 149 ± 6 |
| α | −0.96 ± 0.36 | −1.21 ± 0.07 | −1.30 ± 0.04 |
| β | −2.14 ± 0.14 | −2.8 ± 0.3 | −2.46 ± 0.14 |
| kTBB | 6.39 ± 0.40 | | |
| F (10^{−6} erg cm^{−2} s^{−1}) | 1.6^{+0.05}_{−0.13} | 3.8^{+0.9}_{−0.7} | 7.9 ± 1 |
| Eγ,iso (erg) | 4.19×10^{51} | 1.22×10^{52} | 1.94×10^{53} |
| Lp,iso (erg s^{−1}) | 1.80×10^{51} | 4.44×10^{51} | 1.70×10^{52} |

Figure 4. Prompt emission T90-HR correlations: (a) Time-integrated (shown with a red square), and episode-wise (shown with magenta, blue, and green squares for the first, second, and third episodes, respective) T90-HR correlation for GRB 210204A. We have also shown the data points for long and short GRBs. The vertical black dashed-dotted line indicates the boundary between two classes of GRBs.

3.2 Episode-wise analysis

If we analyse the three pulses separately, we see that the Ep values for the second and third pulses are higher (Table 1). We find that the band function gives acceptable spectral fits to the first and second episodes. The third episode is better fit by a power-law with two breaks (bkn2pow) or by a Band spectrum with an added blackbody component. The thermal component has a temperature of kT = 6.4 ± 0.4 keV. We use the Band + blackbody model in the rest of this section. We note that due to the lower intensity of the first two episodes, the data quality is not high enough to rule out such spectral features in them.

The presence of a thermal component along with a non-thermal...
component indicates a hybrid jet composition, including a matter-dominated hot fireball and a colder magnetic-dominated Poynting flux component for GRB 210204A. The low energy spectral index values (Table 1) are within the range expected for synchrotron emission, $-3/2 < \alpha < -2/3$.

We calculated the $\tau_{90}$ values and the $(50 – 300 \text{ keV})/(10 – 50 \text{ keV})$ hardness ratios for the entire GRB and the three episodes within it. Following Narayana Bhat et al. (2016), we estimated the errors in these by simulating 10,000 light curves by adding Poisson noise with mean equal to observed values and repeating these measurements on each simulated light curve. Figure 4 shows these values compared to the population of long and short GRBs — we find that GRB 210204A, as well as the three individual emission episodes within it, are all consistent with the “long—soft” GRB population.

3.3 GRB global relationships

The time-integrated rest-frame peak energy ($E_{\gamma,i}$) of the prompt emission spectrum of GRBs is correlated to the isotropic equivalent energy ($E_{\gamma,iso}$), and this correlation is defined as Amati correlation (Amati 2006). Basak & Rao (2013) studied the episode-wise Amati correlation for a sample of Fermi-GBM detected GRBs with a measured redshift and confirmed that this correlation is more robust and valid for the episode-wise activity of GRBs. Recently, Chand et al. (2020) studied the Amati correlation for a sample of two-episodic GRBs and found that other than the first episode of GRB 190829A, each episode of two-episodic GRBs are consistent with the Amati correlation. In addition to GRB 190829A, a few other GRBs such as GRB 980425B, GRB 031203A, and GRB 171205 do not follow the Amati correlation.

Another variant of Amati correlation is Yonetoku correlation which is the correlation between time-integrated rest-frame peak energy ($E_{\gamma,i}$) and isotropic peak luminosity $L_{\gamma,iso}$ (Yonetoku et al. 2004). These correlations have been utilised to classify individual episodes in GRBs with long quiescent phases. Figure 5 shows GRB 210204A on the Amati and Yonetoku correlations. We find that the time-integrated, as well as individual episodes values, are consistent with the Amati correlation of typical long GRBs. Similarly, the $L_{\gamma,iso}$ and $E_{\gamma,i}$ Values for individual episodes are consistent with the Yonetoku correlation.

4 AFTERTGLOW

The GRB blast-wave interacts with the circumburst medium giving rise to synchrotron emission, which is one of the primary signatures of standard GRB fireball model (Granot & Sari 2002). The electrons have a power-law energy distribution characterised by the index $p$, which results in the spectral energy distribution, which can be described as a series of multiple power-law segments. These segments join each other a particular frequencies known as break frequencies i.e. self absorption frequency ($\nu_{sa}$), cooling frequency ($\nu_{c}$), and synchrotron frequency ($\nu_{m}$). In optical and X-rays emission, synchrotron self-absorption does not play an important role and hence can be neglected. Depending on the ordering of two break frequencies $\nu_{a}$ and $\nu_{m}$, multiple spectral regimes are possible, which in turn govern the overall shape of the light curve as shown in Granot & Sari (2002, Figure 1). The temporal evolution of these frequencies along with the peak flux $F_{\nu,\text{max}}$ determines the shape of the light curve. We first discuss the evolution of the afterglow, followed by calculation of these quantities after detailed analysis in section 4.2.

4.1 Afterglow evolution

The optical light curve of GRB 210204A shows typical afterglow behaviour — a power-law decline that steepens at some point. The light curve is most densely sampled in the $r$ and $R$ bands; hence we use them for a first-cut analysis. Fitting a power-law to data from these bands from $\sim 1.4$ to 8 days after the burst, we obtain indices $\alpha_r = 1.16 \pm 0.05$ and $\alpha_R = 1.17 \pm 0.04$. The fits are consistent with a constant offset in the two light curves, with $m_R = m_r - 0.24 \pm 0.03$. 

Figure 5. Prompt emission Amati and Yonetoku correlations: (a) Time-integrated (shown with a red square), and episode-wise (shown with magenta, blue, and green squares for the first, second and third episodes, respectively) Amati correlation for GRB 210204A. Note that the $E_{\gamma,i}$ values have been converted to the rest frame using the GRB redshift $z = 0.876$. We also show the data points for long and short GRBs taken from Minaev & Pozanenko (2020). The red and blue solid lines show the best-fit line for long and short bursts, and the shaded regions represent the 2-$\sigma$ uncertainty region for both the populations of GRBs. (b) The episode-wise (shown with magenta, blue, and green squares for the first, second and third episodes, respective) Yonetoku correlation for GRB 210204A. We also show the data points for long and short GRBs taken from Nava et al. (2012). The green and blue solid lines show the best-fit line, and the shaded regions represent the 3-$\sigma$ uncertainty region.
For the rest of the analysis, we scale the $R$ band data to the $r$ band by applying this offset to create a joint $r + R$ light curve.

The common light curve was used to fit a smoothly-joined broken power-law (Laskar et al. 2015) using the formula,

$$ F_r(t) = F_b \left( \frac{(t/t_b)^{-\gamma_1} + (t/t_b)^{-\gamma_2}}{2} \right)^{-1/y} $$

Here $F_b$ is flux at the break, $t_b$ is the time since the GRB at which the break-in-power-law occurs, and the parameter $y$ ensures a smooth transition between the two power-law segments. The combined $r + R$ band light curve with the broken power-law fit is shown in Figure 6. We see a clear jet break early in the light curve, with a shallow temporal power-law index $\alpha_1 \sim 0.33$ at initial times. Due to the free smoothness parameter ($y$), and limited $r$ and $R$ data in early days ($t < 1$ day), the break time is rather poorly constrained to be $t_b = 0.37 \pm 0.30$ d (1-$\sigma$ error). After the jet break within the first day, the decline is steeper with power-law index $\alpha_2 = 1.18 \pm 0.03$.

The light curve shows a significant deviation from the power-law fit at $T - T_0 < 10$ d, seen clearly in the inset in Figure 6. In order to understand these deviations, we first undertake a detailed broadband fit while excluding these days from the data in §4.2, and revisit the residuals in §4.3.

### 4.2 Broadband afterglow modelling

We performed a detailed analysis of the multi-wavelength light curve of the GRB 210204A afterglow using the afterglowpy package (Ryan et al. 2020; Ahumada et al. 2021). The afterglowpy python package is an open-source computational tool to compute the afterglow light curves for the structured jet. It has the capabilities to provide light curves for arbitrary viewing angles. We integrated the afterglowpy with EMCEE (Foreman-Mackey et al. 2013) python package for Markov Chain Monte Carlo (MCMC) routine (Metropolis et al. 1953) to generate the posterior parameters thanks to the fast light curve generation of afterglowpy. We included all radio and X-ray data in our modelling but limited our optical data to $T - T_0 < 8$ d, in order to avoid the “brightening” seen in §4.1.

We used the TopHat jet model in afterglowpy which performs artificial light curve modelling using a standard synchrotron fireball model. The temporal decay index $\alpha$ can be used to calculate the electron power-law index $p$ for the circumburst medium using the closure relation $\alpha = 3(p - 1)/4$ (Li et al. 2020, Table 2). For constant density Inter-Stellar Medium (ISM), the optical and X-ray decays yield $p_{\text{ISM,o}} \sim 2.56$ and $p_{\text{ISM,x}} \sim 2.47$. On the other hand, for a wind-like medium, $\alpha = (3p - 1)/4$, corresponding to unusually low values $p_{\text{wind,o}} \sim 1.91$ and $p_{\text{wind,x}} \sim 0.07$. We can also calculate that spectral index is $\beta ~ 0.75$ using the optical and X-ray fluxes, which in turn gives $p ~ 2.5$: consistent with the constant density ISM case. Hence, we proceed with detailed analysis assuming a constant density ISM.

Assumption of constant density medium (synchrotron Self Absorption is not important as discussed in Section 4) may cause disagreements between the model and the radio data. However, we find that the results do not significantly change whether we include radio in the fits. The MCMC routine was run to fit for angle between the jet axis and the observer ($\theta_{\text{obs}}$), the total energy of the jet ($\log_{10}(E_0)$), the half opening-angle of the jet ($\theta_{\text{core}}$), the circumburst density ($\log_{10}(n_0)$), the power-law index for the electron energy distribution ($p$), and the fraction of energy in electrons and the magnetic field ($\log_{10}(\epsilon_e)$ and $\log_{10}(\epsilon_B)$ respectively). The priors and bounds used for each parameters are shown in Table 2. We assumed a uniform distribution for $\theta_{\text{core}}$ but we took the prior for the observer angle to be uniform in $\sin \theta_{\text{obs}}$ to account for the uniform random orientations of sources in space (see for instance Troja et al. 2018). The exponent $p$ was assumed to be distributed uniformly in the semi-open interval $(2, 4)$: implemented practically as a uniform distribution in $[2.0001, 4]$. Finally, log-uniform priors were used for $E_0$, $n_0$, and $\epsilon_B$. Our preliminary fits showed that the data could not constrain $\epsilon_e$ and $\epsilon_B$ well, so we fixed them at nominal values of $1$ (Ryan et al. 2020) and 0.1 (Panaitescu & Kumar 2002; Gupta et al. 2021a) respectively. The source redshift was held fixed at $z = 0.876$ as discussed in §2.2.2. Inputs for the fitting were the time since an event, observation frequency, measured flux, and the flux uncertainty. afterglowpy was used to generate models for various values of the input parameters, which were then compared to the observed data. The best-fit parameters and the confidence intervals were evaluated by maximising the likelihood of the model fits to the observations.

The one and two dimensional marginal posterior distribution resulted from the routine are shown in Figure A1. For each parameter distribution median posterior and 16% and 84% quantiles are plotted at the top of panel, which we also quote as the parameter bounds here. The model constrained the jet isotropic energy to be $10^{54.06^{\pm 0.03}}$ ergs, consistent with typical long GRB afterglows (Wu et al. 2012). The jet structure parameter ($\theta_{\text{core}}$) and viewing angle ($\theta_{\text{obs}}$) were constrained at $0.024^{+0.003}_{-0.002}$ rad, $0.010 \pm 0.002$ rad respectively. From the values of $\theta_{\text{obs}}$ and $\theta_{\text{core}}$ it is evident that the jet is seen on axis ($\theta_{\text{obs}} < \theta_{\text{core}}$).

The best fit model generated from afterglow + MCMC routine fit is shown in Figure 7. Markers denote observed flux densities, and in several cases, the error bars are smaller than the marker size.

### Table 2. Posterior sampling using MCMC and afterglowpy

| Parameter | Unit | Prior Type | Posterior Parameter Bound |
|-----------|------|------------|---------------------------|
| $\theta_{\text{obs}}$ | rad | sin ($\theta_{\text{obs}}$) | [0.001, 0.8] |
| $\log_{10}(E_0)$ | erg | uniform | 54.06$^{\pm 0.03}$ [48, 56] |
| $\theta_{\text{core}}$ | rad | uniform | 0.024$^{+0.003}_{-0.002}$ [0.01, $\pi$/2] |
| $\log_{10}(n_0)$ | cm$^{-3}$ | uniform | $-5.67^{+0.16}_{-0.15}$ [-6, 100] |
| $p$ | - | uniform | $2.18^{+0.06}_{-0.06}$ [0.0001, 4] |
| $\epsilon_e$ | - | uniform | -0.86$^{+0.17}_{-0.15}$ [-6, 0] |
| $\epsilon_B$ | - | uniform | - |

**Figure 6.** Broken power law fit on r-band afterglow light curve. The red dots depicts the data points in r-band and the solid line is a broken power law fit on the data. The inset shows a zoomed version of the light curve where it shows significant deviation from power-law around $T - T_0 \sim 10$ d.
Figure 7. A multi-band light curve of GRB 210204A afterglow. The multi-band light curve of the GRB 210204A afterglow was fitted to the data using the afterglowpy package integrated with the afterglowpy with E6CEE python package for Markov Chain Monte Carlo (MCMC). Dotted lines show the best fit light curve to each band, and the light coloured band around the dotted line indicates the 16% and 84% quantiles uncertainty in the fitting.

Dashed lines show the light curves in various bands, generated using median values from parameter distribution from MCMC routine. The shaded coloured bands show 16% – 84% uncertainty regions around the median values. The fit indicates that the optical light curve would have risen at very early times, which is plausible based on the values of the synchrotron break frequencies at that time — however, we do not have any observational data to constrain this. Note that the figure shows all data, even the points at $T - T_0 > 8$ d that were excluded from the fit. We can clearly see that the re-brightening episodes have statistically significant deviations from the fit values and are indeed astrophysical in nature.

Next, we tried to estimate the break frequencies and peak time of light curve. For this we consider a spherical shock propagating in a constant density ($n$) medium. The hydrodynamic evolution of this shock can either be radiative or adiabatic, which affects the late-time light curve behaviour. Following Sari et al. (1998), if we model the flux in decaying part of light curve as $F \sim t^{-\beta}$, then the decay index can take two values in the adiabatic case: $\beta_1 = 3(p - 1)/4$ or $\beta_2 = 3p/4 - 1/2$. Using value of $p$ from Table 2, we get $\beta_1 = 0.88$, $\beta_2 = 1.13$. On the other hand, $\beta \sim 3/7$ for fully radiative evolution. In §4.1, we measured this late time decay index to be $\alpha_2 = 1.18 \pm 0.03$: close to the radiative $\beta_2$ calculated here. We conclude that the hydrodynamic shock evolution is adiabatic in nature. Hence, the equations governing shock parameters in the observers’ frame are (Sari et al. 1998):

$$v_c = 2.7 \times 10^{12} \times (1 + z)^{-1/2} E_B^{-1/2} n_0^{-1/2} \text{ Hz}$$

$$v_m = 5.1 \times 10^{15} \times (1 + z)^{1/2} \left( \frac{p - 1/2}{p - 1} \right)^{1/3} E_B^{1/2} \text{ Hz}$$

$$t_m = 2.98 \times (1 + z)^{1/3} \left( \frac{p - 2/3}{p - 1} \right)^{1/3} E_B^{1/3} \nu_{15}^{2/3} \text{ days}$$

$$t_0 = 1.89 \times 10^3 \times (1 + z) \left( \frac{p - 2/3}{p - 1} \right)^2 E_B^2 E_{52} n_0 \text{ days}$$

Here, $t_d$ is time in days since the trigger, $n_0$ is the Interstellar Medium (ISM) density in units of cm$^{-3}$, $E_{52} = E_0/10^{52}$ ergs, $\nu_{15} = \nu/10^{15}$ Hz and $t_m$ is peak time. At $t = t_0$, equation 2 and 3 satisfy $v_0 = v_c(t_0) = v_m(t_0)$ (Sari et al. 1998) where $v_0$ is called critical frequency. $t = t_0$ is the time at which the ejecta transitions from fast cooling to slow cooling phase. Using best–fit values from Table 2, Equation 5 yields $t_0 \sim 3.85 \times 10^6$ days — showing that GRB 210204A transitioned to the slow cooling phase at very early times. This in turn gives a “critical frequency” $v_0 = 2.21 \times 10^{21}$ Hz which lies in $\gamma - \gamma$ ray frequency range as shown by horizontal black dashed line in Figure 8, suggesting that the light curve shown in Figure 7 is a low-frequency light curve (Sari et al. 1998). The optical light curve will peak when the synchrotron frequency ($v_m$) passes through optical bands at $t_m = 0.055$ days $= 4.75 \times 10^8$ s, in agreement with the afterglowpy fits for GRB 210204A shown in Figure 7. However, we lack sufficient early-time data to constrain such a rise. On the other hand, the cooling frequency at ~ 1 day $v_{c,t=1} = 1.68 \times 10^{18}$ Hz,
Various “flare” models to this. We start with a simple Gaussian in §4.2 as a “background” (red dashed lines in Figure 9), and add properties. In all fits, we use the nominal afterglow light curve from level expected from the afterglow model. Measurements are robust, and the data indeed are brighter than the stars, and re-checking the zero points. We find that the photometric return to the original power-law decay. We verified this starting with episodes occur only for a few nights, after which the data seem to be peaked through afterglow modelling of light curve.

Any re-brightening or flaring episode is likely to have an asymmetric profile with a faster rise and slower decline that is not appropriately modelled by a Gaussian function. Hence, we fit them with a more plausible model, the Norris function (Norris et al. 2005). The intensity of the flare is modelled as

$$I(t) = A_1 \exp \left( -\frac{t}{\tau_1} - \frac{(t-t_i)}{\tau_2} \right)$$

(6)

where \(t_i\) is the pulse start time, and the equation holds for \(t > t_i\). The parameters \(\tau_1\) and \(\tau_2\) are associated with the rising and decaying phases of the pulse, but are not directly the rise and decay timescales. The burst intensity is given by the parameter \(A_1\), where \(I = \exp(2\sqrt{\tau_1/\tau_2})\). We ignore the weaker first episode here, but find that the second episode is fit well by Equation 6. The burst “start time” is \(t_i = 88 \pm 3 \times 10^4\). The peak time is \(t_{\text{peak}} = t_i + \sqrt{\tau_1/\tau_2} = (9.9 \pm 2.4) \times 10^5\) s = 11.5 ± 2.7 d — consistent with, but bit sooner than, the values obtained from the double Gaussian fit. The width of the pulse is \(w = \tau_2(1 + 4\sqrt{\tau_1/\tau_2}) = (3.2 \pm 1.4) \times 10^5\) s = 3.7 ± 1.6 d. Under this model, the fluence of the pulse is \(1.48 \times 10^{-9}\) erg cm\(^{-2}\). For comparison, the total fluence of the underlying afterglow model in the same duration is \(1.85 \times 10^{-9}\) erg cm\(^{-2}\).

In summary, we see evidence for two re-brightening episodes in the afterglow, at about 8.8 and 12.7 days after the burst. The second episode is the more significant, with \(\Delta t / t \approx 0.25\) and 0.33, and \(\Delta F / F \approx 1.14\) and 1.07 for the double-Gaussian and Norris models, respectively.

5 DISCUSSION

The afterglow of GRB 210204A is quite typical in early times, following a broken power-law behaviour (§4.1) that is modelled well with as a standard afterglow with afterglow modelling (§4.2). The late-time deviations from a smooth decay (§4.3) can arise from a variety of reasons in long GRB afterglows.

A common cause for a re-brightening is the appearance of the supernova associated with the GRB (§5.1). Flaring may also occur due to patchy shells in the jet (§5.2) or interaction of the jet with inhomogeneities the ISM (§5.3). Various shocks can also cause flaring — for instance a reverse shock in the ejecta (§5.4) or a collision of two forward shocks (§5.5). Delayed activity by the central engine may manifest directly as flaring (§5.6), or interactions between a delayed jet and a cocoon (§5.7), or may refresh the forward shock (§5.8).

We discuss these in detail below, testing each probable cause for the re-brightening in GRB 210204A.

5.1 Supernova

In many long GRBs, the very late-time supernova (SN) bump follows the afterglow emission indicating the collapsar origin for the burst (Galama et al. 1998; de Ugarte Postigo et al. 2017; Roy 2021). To test this possibility, we used the light curve of the prototypical SN 1998bw to compare this excessive emission. As a starting point, we referred to SN 1998bw data from Clocchiatti et al. (2011) and applied a K-correction (Bloom et al. 2001) using redshift of GRB 210204A. Using cubic splines, we interpolated the fluxes into the observed \(r\) band values. A continuous light curve was created using cubic interpolation on these values. The resulted light curves were then further scaled in flux (\(k\), stretch in evolution (\(s\)) and shifted in time (\(S_0\)) to fit GRB 210204A light curve. The SN1998bw model light curve overplotted with the GRB 210204A data is shown in Figure 10. Typical GRB supernovae have absolute magnitudes in the range ~17.5 to ~20 with median value ~ −19.5 mag (Richardson 2009), and peak about ~20 days after the GRB in the rest frame. At the redshift of GRB 210204A, it would correspond to an apparent magnitude of 18 MNRAS 000, 1–18 (2022)
Figure 9. Late-time excessive emission fitting with various models. a) A simple Gaussian fitting to the peak. b) A double Gaussian fit to the late-time variability. c) Norris function fitted on the two peaks for flaring. The solid dark markers shows the data used for fitting for a particular function.

Figure 10. K-corrected SN 1998bw light curve plotted with the excessive emission in GRB 210204A. The dashed red line shows the afterglow model, while the dotted black line shows the afterglow and scaled supernova combined model plotted in the observers’ frame. The scaled supernova-only model (black dashed line) was obtained by scaling SN 1998bw model (blue dashed line) flux up by 7x, stretched to be eight times faster (shorter) than actual, and shifted in time such that the supernova started six days after the GRB. The unscaled SN 1998bw model fitted over the afterglowpy model is shown with blue dotted lines for comparison. This is an unreasonable set of parameters; thus, a supernova cannot explain the re-brightening.

24.6, peaking 38 days after the trigger in the observers’ frame. We note that this is the bolometric magnitude, while our observations are in the r band — corresponding to the rest frame u band. Thus, the expected supernova will be even fainter due to the finite bandwidth and possible extinction. The observed episodes occur much sooner and are much brighter than these values.

Thus, to explain the re-brightening seen in GRB 210204A as a supernova similar to SN 1998bw, the SNe light curve has to be made shorter by a factor of 8 (s = 1/8), the flux has to be made brighter by a factor of k ~ 7, and the supernova onset has to be delayed by ~ 6 days to get a reasonable fit. These parameters — in particular the shorter timescale and delayed onset of the supernova — are quite unphysical, and we do not find any acceptable values that can match the light curve. Hence we conclude that the re-brightening is not associated with a supernova.

5.2 Patchy shell model

The patchy shell model attributes the variability in GRB afterglows to random angular fluctuations in the energy of the relativistic jet (Nakar & Oren 2004). However, such variations are expected at earlier times when there are causally disconnected regions within the jet opening angle. However, the variability caused by this mechanism has timescales Δt > t, (Nakar & Oren 2004; Ioka et al. 2005), inconsistent with our measurements. Therefore, we rule out the patchy shell model as a potential cause for the re-brightening seen in GRB 210204A.

5.3 Variations due to fluctuation in ISM density

Ambient density fluctuations can account for late-time variability in GRB afterglows (Wang & Loeb 2000; Lazzati et al. 2002; Ioka et al. 2005). Such inhomogeneities are primarily caused due to winds from the progenitor or due to turbulence in the ambient medium. Ioka et al. (2005) put an upper limit on flux variation due to inhomogeneities in the ambient medium of standard afterglows for on-axis jets:

$$\frac{\Delta F_{\nu}}{F_{\nu}} \leq \frac{4}{5} \frac{r_c}{\nu_c^2} \frac{F}{\nu F_{\nu}} \frac{\Delta t}{t}$$

(7)

Here f_c ~ (ν_m/ν_c)^(p-2)/2. The light curve of GRB 210204A is governed by slow cooling, with optical-band frequencies satisfying v_m < ν_{opt} < ν_c criteria at time of excessive emission (t ~ 12 days) seen in GRB 210204A light curve (see §4.2). For such cases the F/νF_{\nu} ~ (ν/ν_m)^{(p-3)/2} (Ioka et al. 2005). This suggests ΔF_{\nu}/F_{\nu} < 0.14, which is significantly lower than actual value of 1.07 ~ 1.14 (§4.3). Further, Nakar & Piran (2003) show that assuming a spherically symmetric ISM profiles, any flaring from such interactions will have Δt/t > 1 which is also inconsistent with our measurements. Thus we rule out fluctuations in ambient density as possible origin of flare.

5.4 Reverse-Shock emission in ejecta medium

The interaction of blast-wave and circumburst medium results in two shock waves: the forward shock moving towards circumburst medium and a reverse shock moving back into ejecta itself. The reverse shock could produce an optical peak in the observed optical light curve at early times (Kobayashi & Zhang 2003; Gao et al. 2015; Greiner et al. 2009). Reverse shock is expected to rise rapidly in constant density medium under thin shell approximation case (α_{rise} = 3p - 3/2, where p is the power-law index of the electron distribution), and decline, with α_{decline} = -(27p + 7)/35 (Kobayashi 2000; Greiner et al. 2009). The canonical range of electron distribution index (p) = 2.2 ~ 2.5 (Greiner et al. 2009). The estimated rising and decaying temporal indices of the optical flare are ~ 6.2 and ~ 3.4, respectively. This implies p ~ 2.56 and 4.15 before and after the peak of the flare, respectively. The inconsistent values of p during the rising and
decaying part indicate that the flare is not a result of external reverse shock decay. Moreover, the observed peak time occurs at $t_{\text{peak}} = (9.90 \pm 2.31) \times 10^5$ s post burst, far later than the $10^{3-4}$ s delays expected from flares caused by the reverse shock component in optical bands (Kobayashi & Zhang 2003; Uhm & Beloborodov 2007).

5.5 Collision of two forward shocks

An external collision between shells of GRB can produce flaring on top of afterglow decay (Perna et al. 2006; Zhang et al. 2006; Burrows et al. 2005b; Chincarini et al. 2007). The time and amplitude and duration of such flares vary among GRBs, depending upon the interaction time, Lorentz factor ($\Gamma$) and the energy $E_{\text{los}}$ of the colliding shells. Vlasis et al. (2011) discuss a scenario where a shell with a lower $\Gamma$ is ejected first from the central engine, followed by a shell with a higher $\Gamma$. The first shell decelerates further as it interacts with the interstellar medium, and the second (faster) shell can catch up and ram into the first shell, producing optical flares. For typical GRBs, flares created by such a mechanism should have $\Delta t/t \sim 1$ where $\Delta t$ is the full width at half maximum of the flare, and $t$ is the time at which the flare peaks. We also expect $\Delta F/F \sim 2-5$, where $F$ is the flux of the afterglow and $\Delta F$ is the excess brightening caused by the flare (Vlasis et al. 2011).

The measured $\Delta t/t$ and $\Delta F/F$ values (§4.3) are smaller than the predictions of Vlasis et al. (2011). Thus, we conclude that it is unlikely that collisions between forward shocks caused the late time flaring.

5.6 Late-time flaring emission from central engine

Flaring activity is fairly common in GRB afterglows — seen in more than 50% of the GRBs in X-rays (O’Brien et al. 2006) and ~ 33% of GRB light curves in optical (Swenson et al. 2013). Due to the very limited amount of X-ray data for GRB 210204A, we focus on $r$-band optical observations here — in particular, the second rebrightening episode. Flaring in afterglows may be caused by external shocks caused when the jet interacts with density bumps in the interstellar medium (which is discussed in §5.3), or internal shocks from a central engine that is still active, which we discuss here. Indeed, the presence of the three episodes in the prompt emission of GRB 210204A is itself an encouraging sign that the central engine is capable of injecting energy multiple times. Such central engine activity itself is typically ascribed to two scenarios. The first possibility is a long-lived magnetar, active to late times (Usov 1994; Dai & Lu 1998; Rees & Mészáros 2000). The other possibility is the delayed formation of a black hole in a collapsar, with an accretion disk that may feed matter to the black hole for days (MacFadyen et al. 2001).

Flares are typically characterised by the flaring timescale as compared to the delay time and the fractional increase in flux (Ioka et al. 2005). From §4.3, we have $\Delta t/t \sim 0.25$ and $\Delta F/F \sim 1.4$. These values are consistent with the classical flaring criteria $\Delta t/t \leq 1$ (Swenson et al. 2013; Swenson & Roming 2014). Next, we compare the properties of the flare with the Swenson et al. (2013) sample. Figure 11a shows that the flare is similar to other flares in the duration and flux ratios. What sets it apart is the peak time (Figures 11c). However, this may be an observational bias, as late-time observations by UVOT or other telescopes are not as common.

Based on the long delay after the GRB, the flares are unlikely to be directly associated with late-time central engine activity. However, we cannot fully rule out this possibility due to the lack of multi-wavelength data.

![Figure 11. Comparison of flaring properties of GRB210204A with GRB flares published in Swenson & Roming (2014). The gold, silver and bronze sets are shown by respective colors. GRB 210204A is depicted with red star symbol, with the limits of the error bar indicating the two $\Delta t$ values measured in §4.3. The flare is very similar to other flares in terms of $\Delta F/F$ and $\Delta t/t$, but occurs later than any of the flares in the Swenson & Roming (2014) data set.](image-url)
the burst, but possibly up to $10^4$–$10^5$ s after the event. The flaring in GRB 210204A occurs an order of magnitude later in time, and thus is not any more likely to be caused by interactions between a delayed jet and a cocoon than any other causes of late jet activity discussed in §5.6.

5.8 Refreshed shock

The late-time brightening in the optical light curve could also have originated from a forward shock that is refreshed by late-time energy injection from the central engine (Rees & Mészáros 1998; Panaitescu et al. 1998). Such a refreshed shock scenario has been used to explain the observed re-brightening in the optical light curves of GRB 030329 (Granot et al. 2003) and GRB 120326A (Melandri et al. 2014). Consider a standard forward shock model where the bulk Lorentz factor of the ejecta is not constant but has a range of values. Faster moving shells with higher Lorentz factors ($\Gamma_{\text{fast}} \geq 100$) interact with the surrounding medium first and are slowed down. Slower moving shells ($\Gamma_{\text{slow}} \sim 10$) catch up with these decelerated shells at late times, injecting energy into the shock and increasing the emission. Genet et al. (2006) derived the formula for the collision time of two shells (one moving with $\Gamma_{\text{slow}} \sim 10$ and other moving with $\Gamma_{\text{fast}} \geq 100$) considering the simple assumption (see equation 8),

$$t_{\text{shock}} \approx 1.66 \times \frac{E_{\gamma, \text{iso}, 53}}{\Gamma_{\text{slow}, 10}^{-1/3} \Gamma_{\text{fast}}^{-8/3}} \text{days}$$

In this equation, $E_{\gamma, \text{iso}, 53}$ denotes $E_{\gamma, \text{iso}}/10^{53}$ in erg, $n_0$ is the density for a constant medium which we obtained from broadband afterglow modelling, $\Gamma_{\text{slow}, 10}$ is the bulk Lorentz factor of slow moving shell in the unit of 10. Following the above equation, we calculated the Lorentz factor of the slow moving shell for GRB 210204A at the time of optical brightening. We take $t_{\text{shock}} \sim 12.7$ days from our two-Gaussian fit (§4.3), and substitute $E_{\gamma, \text{iso}, 53} = 10^{4.06}$ erg, $n_0 = 10^{-5.65}$ cm$^{-3}$ from Table 2 to get $\Gamma_{\text{slow}} \sim 32$.

For flares caused by refreshed shocks, we expect $\Delta t/t > 1/4$, broadly consistent with the values measured in §4.3. Thus, a refreshed shock scenario is a plausible explanation for these flares.

6 SUMMARY AND CONCLUSION

We presented a detailed analysis of the prompt emission and afterglow of GRB 210204A. The prompt emission consists of three distinct emission episodes in Fermi-GBM data, separated by quiescent phases. Spectral analysis of the third and brightest episode shows the presence of a thermal component at low energies, adding a member to the small but growing class of GRBs with thermal components. We also find that GRB 210204A (full interval), as well as the individual pulses, are consistent with the Amati relation.

GRB 210204A stands out by having the most delayed flaring activity ever detected in GRBs. A flare is detected 8.8 days after the burst, followed by a stronger flare at 12.7 days. We analyse a multitude of possible causes for such flaring and rule out most of them. We conclude that the flaring is likely caused by late-time activity in the central engine — manifesting either as flares caused due to internal shocks, the interaction of a delayed jet with a cocoon or by refreshing a forward shock.

Such late-time data are not available for most GRBs. It is plausible that more GRBs exhibit such late time flaring activity, but the sample suffers severally from observational biases. This underscores the need for a systematic follow-up program for GRB afterglows. We have undertaken such a program with the GROWTH-India telescope to probe afterglow features in detail.

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APPENDIX A: ADDITIONAL FIGURES FROM AFTERGLOW FITS
Figure A1. Posterior distribution of parameters for model fitted using afterglowpy and EMCEE. The model fit for the $\theta_{\text{obs}}$, $\theta_{\text{core}}$, $\log_{10}(n_0)$, $p$, $\log_{10}(E_0)$, $\log_{10}(\epsilon_B)$ parameters. The histogram shows the 16%, 50% and 84% percentiles of probability distribution.
Table A1: Log of our photometry observations of the optical afterglow of GRB 210204A, taken with various ground-based telescopes.

| JD   | T-T0 (sec) | Filter | Magnitude | Telescope/Instrument |
|------|------------|--------|-----------|----------------------|
| 2459248.74875 | -8273.15200 | r | > 20.87  | P48+ZTF |
| 2459248.76859 | -8655.15520 | g | > 21.34  | P48+ZTF |
| 2459248.83259 | -8109.15136 | i | > 20.22  | P48+ZTF |
| 2459249.71868 | -4471.14816 | g | > 18.74  | P48+ZTF |
| 2459249.79662 | 2262.85056  | r | 17.16 ± 0.03 | P48+ZTF |
| 2459250.71466 | 81581.85216  | r | 19.31 ± 0.06 | P48+ZTF |
| 2459250.75523 | 85086.84960  | g | 19.75 ± 0.08 | P48+ZTF |
| 2459251.72700 | 169047.84672 | r | 19.99 ± 0.08 | P48+ZTF |
| 2459251.73331 | 169592.84928 | i | 19.71 ± 0.10 | P48+ZTF |
| 2459252.89443 | 183513.85056 | g | 20.62 ± 0.2 | P48+ZTF |
| 2459253.72924 | 342044.84928 | i | > 19.80  | P48+ZTF |
| 2459254.82180 | 436438.85184 | i | > 20.70  | P48+ZTF |
| 2459257.80761 | 694412.84448 | i | > 20.00  | P48 + ZTF |
| 2459260.82290 | 954933.84864 | i | > 19.70  | P48+ZTF |
| 2459252.35734 | 223509.45600 | r | 20.55 ± 0.03 | GIT |
| 2459252.30464 | 296715.74400 | r | 20.89 ± 0.03 | GIT |
| 2459252.29448 | 390877.92000 | r | 21.31 ± 0.04 | GIT |
| 2459255.32039 | 479516.97600 | r | 21.72 ± 0.05 | GIT |
| 2459266.24093 | 1423051.63200 | r | > 22.39 | GIT |
| 2459267.194 | 1505396.44800 | r | > 22.30 | GIT |
| 2459271.19364 | 1850965.34400 | r | > 20.81 | GIT |
| 2459272.22723 | 1940267.52000 | r | > 20.57 | GIT |
| 2459274.17682 | 2108712.09600 | r | > 21.69 | GIT |
| 2459275.17860 | 2195266.32000 | r | > 22.0  | GIT |
| 2459252.13277 | 204106.17600 | R | 20.17 ± 0.05 | HCT |
| 2459252.13753 | 204517.44000 | R | 20.16 ± 0.05 | HCT |
| 2459252.14045 | 204769.72800 | R | 20.15 ± 0.03 | HCT |
| 2459252.14231 | 204930.43200 | R | 20.20 ± 0.06 | HCT |
| 2459252.15787 | 206274.81600 | I | 19.77 ± 0.06 | HCT |
| 2459252.16027 | 206482.17600 | I | 19.69 ± 0.04 | HCT |
| 2459252.16265 | 206687.80800 | I | 19.74 ± 0.06 | HCT |
| 2459252.16742 | 207099.93600 | I | 19.78 ± 0.06 | HCT |
| 2459252.37222 | 302552.92800 | R | 20.67 ± 0.05 | HCT |
| 2459253.28418 | 303588.00000 | I | 20.17 ± 0.04 | HCT |
| 2459258.08132 | 718060.89600 | I | 21.30 ± 0.20 | HCT |
| 2459258.10539 | 720140.54400 | V | 22.14 ± 0.11 | HCT |
| 2459260.18751 | 900035.71200 | R | 22.22 ± 0.15 | HCT |
| 2459252.18709 | 208799.84822 | R | 20.19 ± 0.03 | DFOT |
| 2459259.15934 | 811201.82400 | R | 21.86 ± 0.07 | DFOT |
| 2459259.34474 | 827220.38400 | I | 21.60 ± 0.10 | DFOT |
| 2459252.18877 | 208944.96221 | R | 20.22 ± 0.04 | DOT |
| 2459252.19235 | 209255.02675 | R | 20.24 ± 0.04 | DOT |
| 2459252.19528 | 209508.05174 | I | 19.64 ± 0.05 | DOT |
| 2459252.19748 | 209699.10842 | I | 19.68 ± 0.05 | DOT |
| 2459252.20512 | 210359.26022 | V | 20.62 ± 0.05 | DOT |
| 2459252.20909 | 210701.33424 | B | 21.18 ± 0.09 | DOT |
| 2459252.21269 | 211011.89040 | B | 21.30 ± 0.06 | DOT |
| 2459252.21269 | 211011.89213 | B | 21.18 ± 0.08 | DOT |
| 2459252.21669 | 211357.47053 | B | 21.13 ± 0.09 | DOT |
| 2459252.26456 | 215493.34522 | I | 19.67 ± 0.04 | DOT |
| 2459252.26845 | 215829.42480 | R | 20.29 ± 0.05 | DOT |
| 2459252.27239 | 216169.98163 | V | 20.69 ± 0.06 | DOT |
| 2459252.27631 | 216509.06707 | B | 21.13 ± 0.08 | DOT |
| 2459252.27990 | 216819.10569 | B | 21.20 ± 0.09 | DOT |
| 2459252.28421 | 217191.69187 | I | 19.66 ± 0.04 | DOT |
| 2459252.28808 | 217525.78684 | R | 20.37 ± 0.06 | DOT |
| 2459252.29246 | 217903.83609 | V | 20.69 ± 0.06 | DOT |
| 2459252.35158 | 223012.44518 | I | 19.81 ± 0.07 | DOT |
| 2459252.35554 | 223354.01980 | R | 20.34 ± 0.07 | DOT |
Late flaring in GRB 210204A

Table A2: Photometry table of the optical afterglow of GRB 210204A, data obtained from various reported GCNs.

| JD       | T-T0 (sec) | Filter | Magnitude | Instrument | Reference |
|----------|------------|--------|-----------|------------|-----------|
| 2459252.0362 | 195764 | R       | 19.94 ± 0.09 | AZT-33IK | 29417     |
| 2459252.2179   | 211462 | R       | 20.1 ± 0.04   | AS-32    | 29417     |
| 2459252.8472   | 265835 | g       | 21.10 ± 0.10  | LBT      | 29433     |
| 2459252.8472   | 265835 | r       | 20.70 ± 0.10  | LBT      | 29433     |
| 2459252.9761   | 265835 | i       | 20.40 ± 0.10  | LBT      | 29433     |
| 2459252.9761   | 265835 | z       | 20.2 ± 0.10   | LBT      | 29433     |
| 2459252.0930   | 287073 | R       | 20.61 ± 0.04  | AZT-33IK | 29438     |
| 2459252.1607   | 379326 | R       | 20.92 ± 0.05  | AZT-33IK | 29438     |
| 2459252.2961   | 477422 | R       | 21.09 ± 0.08  | DFOT     | 29490     |
| 2459252.3265   | 480047 | R       | 21.4 ± 0.20   | ZTS      | 29499     |
| 2459252.2800   | 648835 | R       | 21.8 ± 0.20   | AS-32    | 29499     |
| 2459252.4186   | 668002 | R       | 21.6 ± 0.30   | AS-32    | 29499     |
| 2459252.1744   | 726104 | R       | 21.66 ± 0.09  | AZT-33IK | 29520     |
| 2459252.1528   | 983436 | r       | 21.86 ± 0.15  | AZT-20   | 29520     |
| 2459252.1110   | 1066228 | R   | 21.8 ± 0.40  | AZT-33IK | 29520     |
| 2459252.2063   | 1074461 | r   | 22.18 ± 0.14 | AZT-20   | 29520     |

Table A3: Log of X-ray observations of the X-ray afterglow of GRB 210204A taken using SwiftXRT in 10 keV band. This data uses a absorption of $0.61 \times 10^{22}\text{cm}^{-2}$ at $z = 0.876$.

| JD       | T-T0 (sec) | Photon Index | Flux Density ($\mu$Jy) |
|----------|------------|--------------|-----------------------|
| 2459251.634 | 161000.965 | $1.61_{-0.20}^{+0.29}$ | 140.99 ± 31.98        |
| 2459251.636 | 161214.462 | $1.62_{-0.25}^{+0.27}$ | 124.61 ± 28.42        |
| 2459251.640 | 161501.848 | $1.65_{-0.20}^{+0.27}$ | 138.95 ± 24.97        |
Table A4: Log of radio data for the radio afterglow of GRB 210204A taken using uGMRT.

| JD       | T-T0 (sec) | Energy-Band | Flux (μJy) |
|----------|------------|-------------|------------|
| 2459266.06 | 1402272.00 | 1254.6 GHz | 140 ± 22   |
| 2459281.09 | 2706011.71 | 1254.6 GHz | 130 ± 20   |
| 2459283.06 | 2876272.416| 647.8 GHz  | 95 ± 45    |

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