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Lack of Bright Supernova Emission in the Brightest Gamma-ray Burst, GRB 221009A

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ABSTRACT

We present photometric and spectroscopic observations of the extraordinary gamma-ray burst (GRB) 221009A in search of an associated supernova. Some past GRBs have shown bumps in the optical light curve that coincide with the emergence of supernova spectral features, but we do not detect any significant light curve features in GRB 221009A, nor do we detect any clear sign of supernova spectral features. Using two well-studied GRB-associated supernovae (SN 2013dx, $M_{r,max} = -19.54$; SN 2016jca, $M_{r,max} = -19.04$) at a similar redshift as GRB 221009A ($z = 0.151$), we modeled how the emergence of a supernova would affect the light curve. If we assume the GRB afterglow to decay at the same rate as the X-ray data, the combination of afterglow and a supernova component is fainter than the observed GRB brightness. For the case where we assume the best-fit power law to the optical

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data as the GRB afterglow component, a supernova contribution should have created a clear bump in the light curve, assuming only extinction from the Milky Way. If we assume a higher extinction of $E(B-V)$=1.74 mag (as has been suggested elsewhere), the supernova contribution would have been hard to detect, with a limit on the associated supernova of $M_{r,max} \approx -19.54$. We do not observe any clear supernova features in our spectra, which were taken around the time of expected maximum light. The lack of a bright supernova associated with GRB 221009A may indicate that the energy from the explosion is mostly concentrated in the jet, leaving a lower energy budget available for the supernova.

Keywords: Gamma-ray bursts (629): individual - objects: GRB 221009A, Supernovae (1668), Photometry (1234), Spectroscopy (1558)

1. INTRODUCTION

Long gamma-ray bursts (GRBs) are thought to be produced by the explosion of very massive stars (Woosley & Bloom 2006; Hjorth & Bloom 2012). These explosions produce relativistic jets where internal dissipation via synchrotron radiation creates prompt emission in γ rays on timescales of seconds. Subsequently, the interaction of the jet ejecta with the ambient medium produces afterglow emission across the electromagnetic spectrum lasting hours to weeks. A few days to weeks after the explosion, an emerging supernova (SN) is often observed as an excess above the afterglow emission.

Long GRBs are often associated with type Ic-BL SNe. Supernovae of this type are core-collapse events where the progenitor star has lost a significant amount of its hydrogen (H) and helium (He) envelope (Filippenko 1997). There are competing, plausible progenitor scenarios for SN Ic-BL, including single Wolf-Rayet stars (Gaskell et al. 1986; Smartt 2009) or binary massive stars (Podsiadlowski et al. 1993; Nomoto et al. 1995), which can explain the stripping of the H and He envelope. However, to date, the progenitors of these SNe have not been definitively identified (see Smartt 2009, for a review). These supernovae have high ejecta expansion velocities of order 15,000-30,000 km s^{-1} (Drout et al. 2011; Modjaz et al. 2011, 2016; Cano et al. 2017) which lead to broad spectra features. Interestingly, only SNe of type Ic-BL have been observed in association with long GRBs, however, many SNe Ic-BL have been observed without a GRB component (Modjaz et al. 2020). The fraction of long GRBs that are accompanied by a SN is still debated. Rossi et al. (2022b) found that for over 1400 long GRBs discovered by Swift through 2022, only 40-50 of them have associated SNe identified via a bump in the optical light curve, and 28 have spectroscopic confirmation. Dado & Dar (2018) found that for low redshifts, the number of GRBs with an associated supernovae is comparable to GRBs without supernovae.

However, where deep spectroscopic observations are possible (low z cases), there are only 4 GRBs with no associated supernovae: GRB 060505 (Fynbo et al. 2006), GRB 060614 (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006), GRB 111005A (Michałowski et al. 2018; Tanga et al. 2018), and GRB 211211A (Rastinejad et al. 2022; Troja et al. 2022, which instead showed potential kilonova emission). For GRBs without deep spectroscopic observations, the identification of a supernova bump in the lightcurve based purely on photometry can be challenging, and often depends sensitively on the assumptions made when modeling the GRB afterglow. For example, Melandri et al. (2022) presented the results of a SN connected to the GRB190114C (the first GRB with detected TeV emission) using various facilities, including HST. They find a large range in the probable luminosity of the associated supernova SN 2019jrj, largely due to uncertainties in estimating the time of the GRB jet break. Their study shows that late-time photometry is critical for constraining the jet break time, which in turn helps to constrain the energy of the SN explosion connected to the GRB.

The recent GRB 221009A (RA (J2000)= 19:13:03.50, Dec (J2000) = +19:46:24.23; Laskar et al. 2022), at a redshift of z = 0.151 (de Ugarte Postigo et al. 2022; Castro-Tirado et al. 2022), provides a unique opportunity to explore GRB physics in detail. In contrast to many other nearby GRBs, which are often underluminous compared to more distant "cosmological" GRBs at $z > 1$ (Dainotti et al. 2022), GRB 221009A is the brightest GRB to ever be detected by the Fermi Gamma-ray Burst Monitor (GBM) (Veres et al. 2022) and has generated broad community interest.

It is also one of a very small number of GRBs with detected very high energy emission, with reports of photon energy reaching 18 TeV by the LHAASO group (Huang et al. 2022) and 251 TeV by Carpet-2 (Dzhappuev et al.

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2022). The detection of very energetic photons in the TeV range such as in the case of GRB 190114C (MAGIC Collaboration et al. 2019) and now GRB 221009A, challenges our understanding of GRB physics. There is no firm consensus on the production mechanisms of these very high-energy photons in the range of GeV to TeV (see further discussions in Balaji et al. 2023; Mirabal 2023). Atteia (2022) have predicted that the next event like GRB 221009A has a 10% probability of being observed in the next 50 years.

There is an ongoing large follow-up campaign using various ground-based telescopes covering the entire electromagnetic spectrum for GRB 221009A. Here, we present an extensive search for SN emission in GRB 221009A, focusing on the optical bands. First, we present the observations in Section 2. Results from photometric and spectroscopic observations are provided in Section 3. Finally, we discuss the implications of these observations, along with concluding remarks, in Section 4. Throughout this paper, we use UTC date and time. We assume a Λ Cold Dark Matter Universe with $H_0 = 70$ kms^{-1}Mpc^{-1}, $\Omega_m = 0.286$, and $\Omega_\lambda = 0.714$ (Bennett et al. 2014). Presented uncertainties are at the 1σ confidence level.

The extinction towards GRB 221009A is high, as it is at a Galactic latitude of b=4.3° and may also include a host component and/or a component associated with the local environment of the explosion. The assumed extinction value can affect interpretations of any underlying supernova component of the GRB. Throughout this paper, we present photometric and spectroscopic data that have been corrected for extinction towards GRB 221009A using two different values. First, we use a $E(B-V) = 1.32 \pm 0.06$ mag, representing a Milky Way-only extinction scenario (using Schlafly & Finkbeiner 2011). Second, we use a higher $E(B-V) = 1.74$ mag value, as recently motivated by Fulton et al. (2023). Throughout the paper, we assume $R_v = 3.1$. We discuss the implications for any supernovae emission for each of these scenarios.

2. OBSERVATIONS AND DATA REDUCTION

Following the discovery of GRB 221009A (Fig. 1), we started an extensive ground-based follow-up campaign with the aim of detecting the SN associated with the GRB. We augment this dataset with public archival data from the Hubble Space Telescope (HST) and the results reported to the GCN service.

2.1. *Photometry*

In Fig. 2 we present the photometric light curve of GRB 221009A from our own observations along with optical/NIR data from GCN circulars and publicly available data from HST.

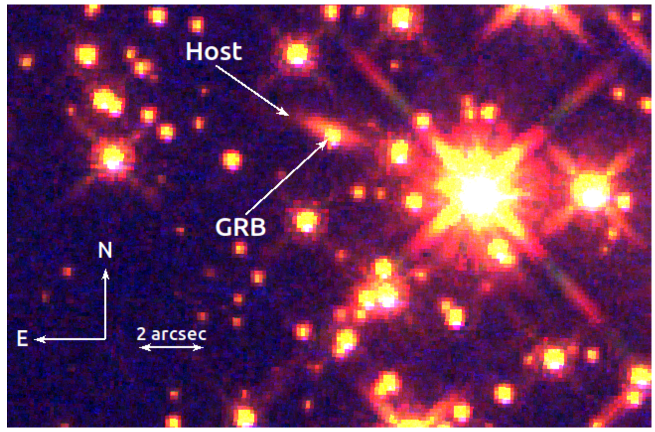

Figure 1. Combined HST images WFC3/UVIS and WFC3/IR (F625W, F125W, F160W) of the GRB 221009A field, observed on 2022 Dec. 04. Note the clear appearance of an underlying host galaxy, with a disk-like morphology. GRB 221009A is slightly offset from the center of the apparent host, off the disk plane.

2.1.1. *Ground-based Optical Observations*

We performed optical photometric follow-up using the following instruments: the Multi-Object Double CCD Spectrographs/Imagers (MODS; Pogge et al. 2010) on the Large Binocular Telescope (LBT; 8.4 m twin telescope at Mt. Graham, Arizona), MuSCAT3 (Narita et al. 2020) on the Faulkes Telescope North (Brown et al. 2013) (FTN; 2 m telescope at Haleakalā Observatory, Hawaii) using Global Supernova Project time, Binospec (Fabricant et al. 2019a) on the MMT (6.5 m telescope at Mt. Hopkins, Arizona), and the Goodman High-Throughput Spectrograph (GHTS; Clemens et al. 2004) on the Southern Astrophysical Research Telescope (SOAR; 4.1 m telescope at Cerro Pachón, Chile). Finally, GRB 221009A was observed by the Dark Energy Camera (DECam; Flaugher et al. 2015) instrument on the 4-m Blanco Telescope at CTIO as a target of opportunity as part of the DECam Local Volume Exploration (DELVE) survey (Drlica-Wagner et al. 2021, 2022). The details of the instruments and exposure times used, along with the observed magnitudes in different filters, are presented in Table 1.

Images from Las Cumbres Observatory and DECam were preprocessed using BANZAI (McCully et al. 2018) and the DECam Community Pipeline (Valdes et al. 2014), respectively. We bias subtracted and flat-fielded the remaining images using Python. We then performed aperture photometry using the Astropy Photutils package (Bradley et al. 2019) and calibrated to the Pan-

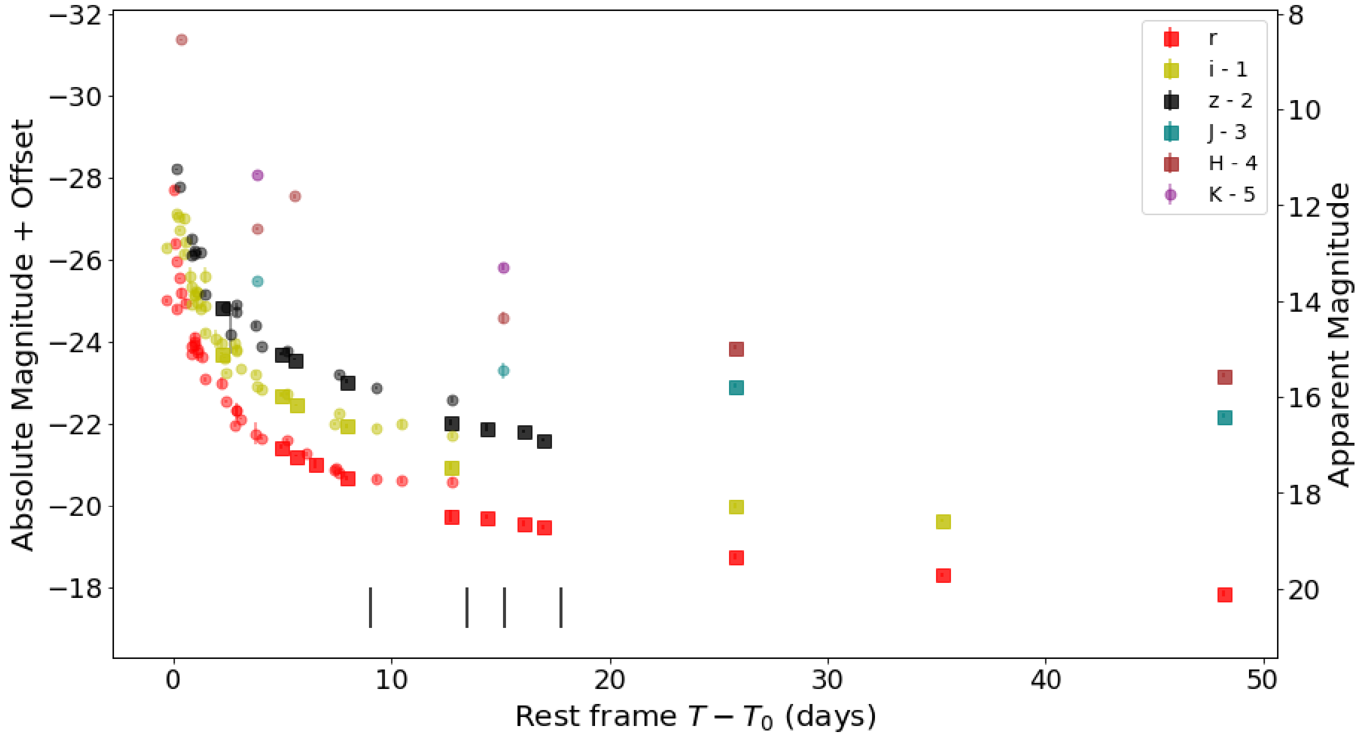

Figure 2. Optical light curve data in r, i, z, J, H, K filters from GCN (in circles) and data reduced by our group (shown in squares). These values are from Tables 1, 2 and 3 and corrected for Galactic extinction. The vertical black lines correspond to the time of our spectral observations.

STARRS1 catalog (Chambers et al. 2016). Table 1 and Fig. 2 present all of our optical and NIR photometry.

2.1.2. *HST data*

We obtained publicly available data from Mikulski Archive for Space Telescopes (MAST) on GRB 221009A taken with the Wide-Field Camera 3 (WFC3; Dressel 2022) UVIS and IR channel on HST on three epochs, 2022-11-08, 2022-11-19, and 2022-12-04, and measured photometry on the calibrated and combined optical and NIR images (Program 17264, PI: A. J. Levan). In Table 2, we present our HST photometric results and other information. Photometry for the first epoch of HST data were also circulated via GCN by Levan et al. (2022); our measurements are in good agreement within the respective errors. We assume the HST filters F625W, F775W, F098M, F125W, and F160W correspond to r, i, y, J, H filters respectively. The results from our reductions are included in Fig. 2. We note that the last two HST NIR data points could be contaminated due to the host galaxy.

2.1.3. *GCN*

We collected all optical and NIR data reported via the GCNs for GRB 221009A, and optical data are presented in Table 3. As we are looking for subtle changes in brightness, consistent filter throughputs and photometric systems are essential to this analysis. For this reason, we decided to only make use of data that have been reported in AB magnitudes and calibrated to the Pan-STARRS1 catalog (Chambers et al. 2016), for consistency. We corrected these data for Galactic extinction ($E(B-V) = 1.32$ mag and $E(B-V) = 1.74$ mag) before performing the data analysis.

2.2. *Spectroscopy*

We took our first optical spectrum of GRB 221009A 10.4 days after the BAT trigger with the 10 m Hobby-Eberly Telescope (HET; Ramsey et al. 1998; Hill et al. 2021; Shetrone et al. 2007) using the red arm of the Low-Resolution Spectrograph-2 (LRS2-R) having a $12'' \times 6''$ integral field unit and covering the 6450–8470 Å wavelength interval with a resolution of $R \sim 1800$ (Chonis et al. 2016). Sky subtraction and wavelength and flux calibrations were performed by applying the Panacea[1] pipeline implemented at HET. Further details on the instrument configuration and the standard data reduction steps can be found in Yang et al. (2020).

[1] https://github.com/grzeimann/Panacea

Table 1. GRB 221009A ground-based photometric data

Date (UT)	MJD	Facility	Instrument	$t - t_0$ (days)	Exposure (s)	r (mag)	i (mag)	z (mag)	GCN
2022-10-12	59864.11	LBT	MODS	2.5	6×120	···	19.00 ± 0.02	18.26 ± 0.01	32759[a]
2022-10-15	59867.27	FTN	MuSCAT3	5.7	3×300	21.13 ± 0.06	20.05 ± 0.05	19.39 ± 0.05	32771[b]
2022-10-15	59867.99	CTIO	DECam	6.4	1×180	21.34 ± 0.03	20.25 ± 0.02	19.52 ± 0.02	···
2022-10-17	59869.03	SOAR	GHTS	7.4	3×180	21.53 ± 0.10	20.42 ± 0.10	19.75 ± 0.12	···
2022-10-18	59870.75	FTN	MuSCAT3	9.2	3×300	21.88 ± 0.06	20.77 ± 0.04	20.06 ± 0.04	···
2022-10-24	59876.20	FTN	MuSCAT3	14.6	3×300	22.82 ± 0.15	21.76 ± 0.10	21.07 ± 0.07	···
2022-10-26	59878.10	MMT	Binospec	16.5	16×30	22.83 ± 0.07	···	21.19 ± 0.08	···
2022-10-28	59880.07	MMT	Binospec	18.5	16×30	23.00 ± 0.07	···	21.29 ± 0.04	···
2022-10-29	59881.07	MMT	Binospec	19.5	16×30	23.08 ± 0.06	···	21.50 ± 0.04	···

NOTE—No correction for Galactic extinction has been applied.

[a] Shrestha et al. 2022a

[b] Shrestha et al. 2022b

Table 2. HST public data of GRB 221009A.

Date (UT)	MJD	$t - t_0$ (days)	Instrument	F625W	F775W	F098M	F125W	F160W
2022-11-08	59891.27	29.68	WFC3	23.79 ± 0.32	22.72 ± 0.26	21.10 ± 0.08	20.49 ± 0.05	20.14 ± 0.05
2022-11-19	59902.18	40.59	WFC3	24.24 ± 0.51	23.08 ± 0.40	···	···	···
2022-12-04	59917.06	55.46	WFC3	24.70 ± 0.38	···	21.82 ± 0.11	21.21 ± 0.07	20.83 ± 0.07

NOTE—No correction for Galactic extinction has been applied. The F625W and F775W filters are from WFC3/UVIS, while the F098M, F125W, and F160W filters are from WFC3/IR.

Furthermore, we observed the location of GRB 221009A using the Binospec imaging spectrograph on the MMT (Fabricant et al. 2019b) for three different epochs. We used a long slit with a width of 1″. For the observations done on 2022-10-25 (+15.48 days) and 2022-10-30 (+20.47 days), the 270 line mm^{-1} grating was used with central wavelengths of 6500 Å and 7500 Å, respectively, as presented in Table 4. For the 2022-10-27 (+17.49 days) observation, we used the 600 line mm^{-1} grating with a central wavelength of 7500 Å. We performed the initial data processing of flat-fielding, sky subtraction, and wavelength and flux calibration using the Binospec IDL pipeline (Kansky et al. 2019).[2] 1D spectra were extracted employing standard procedures using the Image Reduction and Analysis Facility (IRAF [3]). To account for slit losses, we scaled the spectrum to match the photometric data of GRB 221009A using a Python routine from Hosseinzadeh & Gomez (2022). Finally, we corrected the spectrum for Galactic extinction using the Python `extinction` package (Barbary 2016).

A log of our spectroscopic observations can be seen in Table 4, and the spectra can be seen in Figure 7 after correction for extinction and subtraction of an afterglow component as discussed in Section 3.2

[2] https://bitbucket.org/chil_sai/binospec/wiki/Home

[3] IRAF (Tody 1986, 1993) was distributed by the National Optical Astronomy Observatory, which was managed by the Association of Universities for Research in Astronomy (AURA) under a co-operative agreement with the National Science Foundation.

3. SUPERNOVA LIMITS

The observation of SN 1998bw coincident spatially and temporally with GRB 980425 (Galama et al. 1998; Iwamoto et al. 1998; Kulkarni et al. 1998) was the first direct evidence of the GRB-SN association. For nearby (z<0.3) long GRBs, such as GRB 221009A, there have been observations of an associated SN (Hjorth & Bloom 2012) in all except four cases: GRB 060505 (Fynbo et al. 2006), GRB 060614 (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006), GRB 111005A (Michałowski et al. 2018; Tanga et al. 2018), and

Table 3. GCN Photometric data of GRB 221009A

GCN	Telescope	$t - t_0$(days)	r (mag)	i (mag)	z (mag)	J (mag)	H (mag)	K (mag)	Reference
32647	NEXT	0.0087	14.93 ± 0.05	⋯	⋯	⋯	⋯	⋯	Xu et al. (2022)
32645	AZT-33IK	0.01223	14.84 ± 0.09	⋯	⋯	⋯	⋯	⋯	Belkin et al. (2022c)
32662	GIT	0.094	16.16 ± 0.07	⋯	⋯	⋯	⋯	⋯	Kumar et al. (2022)
32646	MeerLICHT	0.17	17.76 ± 0.08	15.58 ± 0.03	14.89 ± 0.03	⋯	⋯	⋯	de Wet et al. (2022)
32644	BOOTES-2/TELMA	0.19	16.57 ± 0.02	⋯	⋯	⋯	⋯	⋯	Hu et al. (2022)
32638	LT	0.29	17.00 ± 0.03	15.98 ± 0.03	15.32 ± 0.03	⋯	⋯	⋯	Perley (2022)
32755	REM	0.4	⋯	⋯	⋯	⋯	12.62 ± 0.02	⋯	D'Avanzo et al. (2022)
32652	REM	0.434	17.36 ± 0.12	⋯	⋯	⋯	⋯	⋯	Brivio et al. (2022)
32664	CDK	0.54	⋯	15.70 ± 0.13	⋯	⋯	⋯	⋯	Romanov (2022a)
32659	LOAO	0.63	17.55 ± 0.06	16.41 ± 0.05	⋯	⋯	⋯	⋯	Paek et al. (2022)
32669	Nickel	0.65	17.6 ± 0.1	16.3 ± 0.1	⋯	⋯	⋯	⋯	Vidal et al. (2022)
32730	Mitsume	0.9320	⋯	17.1 ± 0.2	⋯	⋯	⋯	⋯	Sasada et al. (2022)
32729	AZT-33IK	1.02	18.84 ± 0.02	17.8 ± 0.02	16.99 ± 0.02	⋯	⋯	⋯	Zaznobin et al. (2022)
32667	SLT-40cm	1.04	18.67 ± 0.16	17.38 ± 0.09	16.60 ± 0.09	⋯	⋯	⋯	Chen et al. (2022)
32795	GRANDMA	1.1360	18.57 ± 0.05	17.56 ± 0.05	16.93 ± 0.05	⋯	⋯	⋯	Rajabov et al. (2022)
32684	Sintez-Newton	1.163	18.43 ± 0.10	⋯	⋯	⋯	⋯	⋯	Belkin et al. (2022b)
32670	AZT-20	1.164	18.64 ± 0.03	17.58 ± 0.01	16.87 ± 0.05	⋯	⋯	⋯	Kim et al. (2022)
32693	Las Cumbres 1 m	1.22	18.80 ± 0.21	17.8 ± 0.2	⋯	⋯	⋯	⋯	Strausbaugh & Cucchiara (2022a)
32709	RC80	1.26	18.74 ± 0.12	17.5 ± 0.08	⋯	⋯	⋯	⋯	Vinko et al. (2022)
32678	BG3-Opal	1.48	⋯	17.92 ± 0.06	16.92 ± 0.05	⋯	⋯	⋯	Groot et al. (2022)
32679	T24 iTelescope	1.66	⋯	17.1 ± 0.2	⋯	⋯	⋯	⋯	Romanov (2022b)
32705	COATLI	2.63	⋯	19.10 ± 0.02	⋯	⋯	⋯	⋯	Butler et al. (2022)
33038	FTN	2.73	20.01 ± 0.03	19.48 ± 0.03	18.26 ± 0.01	⋯	⋯	⋯	Kimura et al. (2022)
32727	GMG	3.0	⋯	⋯	18.9	⋯	⋯	⋯	Mao et al. (2022)
32753	T120cm	3.25	20.23 ± 0.09	18.91 ± 0.11	18.35 ± 0.13	⋯	⋯	⋯	Schneider et al. (2022)
32743	RTT-150	3.3	20.24 ± 0.19	18.92 ± 0.04	18.10 ± 0.04	⋯	⋯	⋯	Bikmaev et al. (2022a)
32738	Las Cumbres 1 m	3.53	> 21	> 20.5	⋯	⋯	⋯	⋯	Strausbaugh & Cucchiara (2022b)
32739	LDT	3.57	20.44 ± 0.02	19.37 ± 0.01		⋯	⋯	⋯	O'Connor et al. (2022a)
32752	RTT-150	4.3	20.86 ± 0.27	19.50 ± 0.07	18.70 ± 0.06	⋯	⋯	⋯	Bikmaev et al. (2022b)
32750	Gemini	4.4	⋯	⋯	⋯	17.93 ± 0.03	17.23 ± 0.05	16.69 ± 0.02	O'Connor et al. (2022c)
32749	Gemini	4.437	⋯	19.8	⋯	⋯	⋯	⋯	Rastinejad & Fong (2022)
32758	Pan-STARRS1	4.67	20.92 ± 0.05	19.88 ± 0.02	19.21 ± 0.02	⋯	⋯	⋯	Huber et al. (2022)
32769	AZT-20	6.05	20.96 ± 0.05	20.00 ± 0.04	19.31 ± 0.08	⋯	⋯	⋯	Belkin et al. (2022a)
32804	TNG	7.3	⋯	⋯	⋯	⋯	16.45 ± 0.04	⋯	Ferro et al. (2022)
32809	LBT	8.58	21.63 ± 0.02	⋯	⋯	⋯	⋯	⋯	Rossi et al. (2022a)
32799	LDT	9.5	21.68 ± 0.07	20.72 ± 0.05	⋯	⋯	⋯	⋯	O'Connor et al. (2022b)
32818	AZT-20	12.05	21.94 ± 0.07	20.72 ± 0.11	⋯	⋯	⋯	⋯	Belkin et al. (2022c)
32860	Gemini	17.4	⋯	⋯	⋯	20.1 ± 0.2	19.43 ± 0.15	18.94 ± 0.08	O'Connor et al. (2022d)
32921	HST	29.68	23.61 ± 0.04	22.43 ± 0.04	⋯	⋯	⋯	⋯	Levan et al. (2022)

Note—No correction for Galactic extinction has been applied.

GRB 211211A (Rastinejad et al. 2022; Troja et al. 2022). However, the true fraction of long GRBs without a SN is unknown (Hjorth & Bloom 2012). The study of associated SNe provides an important clue to the understanding of the progenitors and environment of these long GRBs. Thus, we search for supernova signatures in our GRB 221009A light curves and spectra in Subsection 3.1 and Subsection 3.2, respectively.

3.1. *Light Curve Analysis*

For our light curve analysis, we focused on the r and i bands because we have better data coverage in these bands compared to z band. The emission observed at the GRB position will have contributions from three potential components: the GRB afterglow, the supernova, and the host galaxy. The host galaxy is faint and only visible in the NIR (Figure 1), and we do not explicitly model its contribution, although it may contaminate our results at a low level. That said, we do consider two extinction scenarios as discussed earlier, with one focused solely on Milky Way extinction ($E(B-V)$=1.32) and another which may include a host galaxy contribution ($E(B-V)$=1.74; Fulton et al. 2023). We approached the search for the associated SN component using two different techniques.

For the first technique, we model the GRB optical afterglow using a broken power law model, assuming the decay index from the XRT data to avoid possible supernova contamination in the optical data (e.g. Toy et al. 2016; Fulton et al. 2023). The reduced χ^2 for a one-break fit of the XRT data is 1.33 whereas for four breaks (the best-fit model) is 1.24. Although the best-fit model includes four breaks, we do not find a significant improvement in the fit beyond one break and thus use a one-break model for the remainder of the analysis. The one-break fit of the XRT data has a decay index of $\alpha_1 = 1.515 \pm 0.003$ before the break time of 0.6 days and after the break the decay index is $\alpha_2 = 1.663 \pm 0.006$[4] (Evans et al. 2009). The solid purple line represents this decay index in Fig. 3 and Fig. 4. Hence, we force the decay index after 0.6 days for optical data to be 1.663 ± 0.006 which is the α_2 and are labeled 'XRT BPL' in Fig. 3 and Fig. 4.

We also fit all the optical data points with an empirical broken power law, whose best-fit is represented by the solid red and yellow lines for the r and i filters, respectively. The best-fit model to the optical data gives the decay index values of 0.64 before and 1.44 after the break time of 0.6 days for the r band data. For the i band data, the best-fit model has decay index values of 0.81 before and 1.46 after the break time of 0.6 days. These broken power-law fits to the optical data are labeled 'GRB BPL' in Fig. 3 and Fig. 4.

In addition to the power-law fits above, we consider an additional supernova component using data directly from two supernovae associated with GRBs: SN 2013dx/GRB 130702A (Toy et al. 2016) and SN 2016jca/GRB 161219b (Cano et al. 2017). SN 2013dx ($M_{r,max}$=−19.54) is at a redshift of 0.145 and SN 2016jca ($M_{r,max}$=−19.04) is at a redshift of 0.1475, both of which are similar to the redshift of GRB 221009A; these objects were specially chosen so that we could do direct filter comparisons between them and GRB 221009A without any K correction. These comparisons in the r and i bands are presented in Fig. 3 and Fig. 4 respectively. Each row in this figure represents a model for one supernova, where the black solid line is the supernova light curve.

In order to determine the effect of the supernova on the light curve of GRB 221009A we combined the afterglow component (purple solid line) with the supernova component (black solid line). The resulting light curve is shown as a dashed line in the plot. For the case with a lower extinction value (left panels of Fig. 3 and Fig. 4), the dashed lines initially underpredict the flux compared to the observed flux. This can be also seen in the residual plots shown in the bottom panels. During the SNe peak, the match to the observed data is better. However, in the r band we find an excess in observed flux compared to the X-ray power law + SN model. For the case of $E(B-V) = 1.74$ mag, the dashed lines underpredict the flux compared to observed data at all times. The residual plots for all the cases show that the broken power law fitted to optical data produces the least residual, without any need for a SN component.

For the second method, we assume that the optical light curve is dominated by the GRB afterglow and it is defined by the broken power law fit to the optical data. As seen in the earlier discussion, this gives the least residual. In addition, the optical decay index in r band after the break is $\alpha_{opt,r} = 1.44$ and for i band is $\alpha_{opt,i} = 1.46$. The decay index for XRT is $\alpha_X = 1.663$. We see that the difference between the optical and X-ray decay indices is close to 1/4, which is expected for the slow cooling regime for constant interstellar medium for the case where the synchrotron cooling break is between the optical and the X-ray band (Zaninoni et al. 2013). Laskar et al. (submitted) show that an afterglow model with a wind-like density profile can also match the optical and X-ray light curves without the addition of a SN component. In their model, the cooling break is above

[4] https://www.swift.ac.uk/xrt_live_cat/01126853/

Table 4. Spectroscopic Observations

UT Date	MJD	Facility	Instrument	Filter	Grating	$t - t_0$ (days)	Exposure (s)
2022-10-21	59873.10	HET	LRS2-R	···	VPH-Grism	10.40	1×2000
2022-10-25	59877.07	MMT	Binospec	LP3800	270	15.48	4×1200
2022-10-27	59879.08	MMT	Binospec	LP3800	600	17.49	5×1200
2022-10-30	59882.06	MMT	Binospec	LP3800	270	20.47	4×1200

the X-ray band and the characteristic synchrotron frequency (corresponding to the minimum electron energy) is just below the optical band, which causes the optical light curves to decline more slowly than the X-rays. With this assumption, we investigated the effect of an associated SN in the light curve. We add the contribution of SN 2013dx and SN 2016jca to the GRB afterglow model with broken power law and decay index of 1.44 and 1.46 after the break for r and i bands respectively. For the case of $E(B-V) = 1.32$ mag, we see that both in r (Fig. 5) and i (Fig. 6) bands, a supernova bump would have been clear for both the SNe cases. However, if the $E(B-V)$ is high as 1.74 mag, then the bump is not clear in the light curves and it could be hidden by the afterglow. This gives us a limit of $M_{r,max} \approx -19.54$ mag.

3.2. *Spectroscopic Analysis*

We observed the location of GRB 221009A spectroscopically using the HET and MMT. The observations were taken at four different epochs to detect the broad spectral features which are observed in type SNe Ic-BL associated with GRBs. In Fig. 7, we present the results of spectroscopic observations done at the location of GRB 221009A on four different epochs using HET and MMT after smoothing. The spectra have been corrected for two different extinction values of $E(B-V) = 1.32$ mag (left panel) and $E(B-V) = 1.74$ mag (right panel). We note tentative, narrow Hα emission at $z = 0.151$ in the +17.8 day spectrum, which may also be visible in the +10.4 day HET spectrum; we take this as tentative confirmation of the host redshift.

We also attempted to isolate the supernova features in these spectra by modeling the contribution of the GRB afterglow in the spectra. To model the GRB afterglow contribution, we used the analytic function $F_\nu \propto t^{-\alpha}\nu^{-\beta}$ where F_ν is the flux, ν is the frequency, β is the spectral index, t is the time since trigger, and α is the photometric decay index. We used our data in the r, i, and z filters from day 6.4 and $E(B-V) = 1.32$ to fit a power law and calculate the spectral decay index. We found $\beta_{\rm opt} = 0.59 \pm 0.17$, which we then used to calculate the flux. We note that our calculated spectral index does not follow $\beta_{\rm X} = \beta_{\rm opt} + 0.5$, where $\beta_{\rm X} = 0.9$ is the spectral index from XRT data. We calculated F_ν for the times of each observed spectrum and we performed photometric calibration to extinction-corrected ($E(B-V) = 1.32$ mag and $E(B-V) = 1.74$ mag) broadband photometry. Finally, we subtracted this contribution from the original spectra to extract supernova features. We do not detect any clear supernova features such as a broad absorption feature of Si II λ6355 even after this correction in our spectra.

We also compared the spectra of GRB 221009A to two different supernovae, SN 1998bw (Patat et al. 2001) and SN 2006aj, associated with GRB 980425 and GRB 060218 (Modjaz et al. 2006; Pian et al. 2006) respectively. We selected these two cases because SN 1998bw is a bright SN associated with GRB where as SN 2006aj falls in the lower luminosity category. We obtained their spectra from the Weizmann Interactive Supernova Data Repository (Yaron & Gal-Yam 2012) at similar phases to our spectra. The SN 1998bw spectra in WISeREP were from Patat et al. (2001) and those for SN 2006aj were from Modjaz et al. (2006); Pian et al. (2006). These spectra from the archive were first corrected for the Galactic extinction $E(B-V)$ of 0.0509 mag and 0.1253 mag for SN 1998bw and SN 2006aj, respectively. We also shifted the spectra from the redshifts of 0.0085 and 0.0331 for the two supernovae to the redshift of GRB 221009A of 0.151. Finally, these redshifted spectra were scaled to match to extinction-corrected photometry of GRB 221009A. The comparison between the calibrated spectra and the spectra of GRB 221009A at four different epochs is presented in Fig. 8. For both the SN 1998bw and SN 2006aj spectra, broad features indicative of SN Ic-BL type can be seen for all the epochs. However, the GRB 221009A spectra are noisier than the SN 1998bw and SN 2006aj spectra. At the first epoch i.e. 10.40 days after the GRB trigger, our HET spectrum when corrected for $E(B-V) = 1.74$ (blue line in Fig. 8) has a similar structure as the other two supernovae. However, there are no distinct broad absorption features as expected for SN Ic-BL. MMT

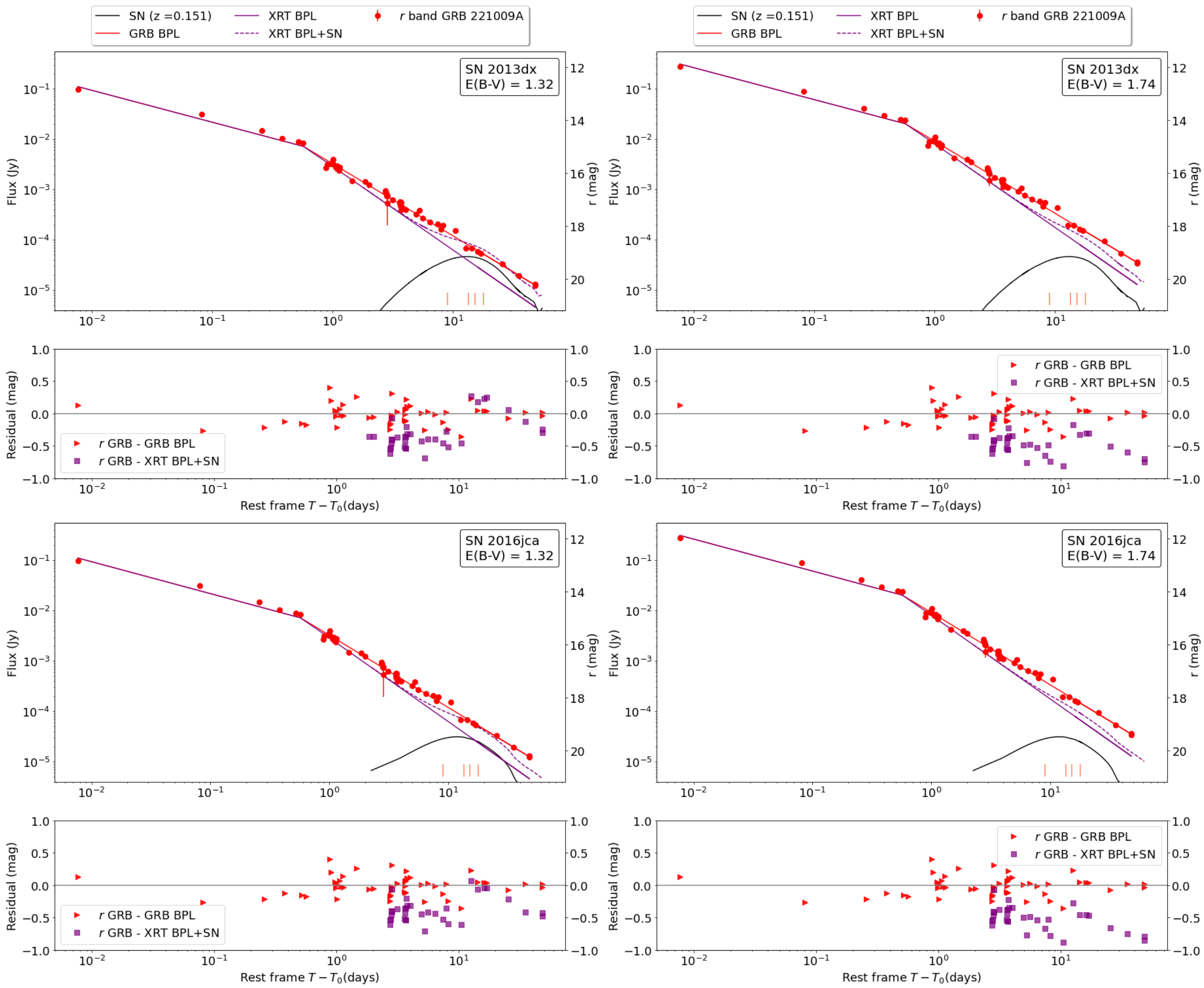

Figure 3. Light curves for the r filter for two different extinction values of $E(B-V) = 1.32$ mag (left) and $E(B-V) = 1.74$ mag (right) with a broken power-law fit to the data. Light curves models of SN 2013dx (top) and SN 2016jca (bottom) are included as black solid lines along with GRB data. For each case, a residual plot in magnitude is presented. The purple square points are the difference between supernova contribution plus GRB afterglow estimated by the XRT decay index and broken-power-law estimate. The red triangle points are the difference between the observed GRB magnitude and broken-power-law estimate. The orange lines in the figure are the epochs we have spectroscopic observations. The residual plot shows that the SN component is not necessary to explain the light curve.

spectra at 15.48 days and 17.79 days after the trigger do not show any clear features. For the last spectrum at 20.47 days after the trigger observed by MMT, there is a broad feature with some noise between 6000 and 6500 Å similar to the other two SNe. However, we do not see clear broad absorption features which are indicative of the SN component. We also note that Fulton et al. (2023) reported that the peak of the supernova they find associated with the GRB 221009A is 20 days after the trigger, the same as the epoch of our last spectral observation.

4. DISCUSSIONS AND CONCLUSION

For this work, we observed the location of GRB 221009A both using imaging and spectroscopy to search for supernova signatures. We made our first observations using the LBT MODS imager starting 2.5 days after the BAT trigger and augmented our photometry with publicly available data from GCN and HST to do our photometric analysis. Our light curve modeling

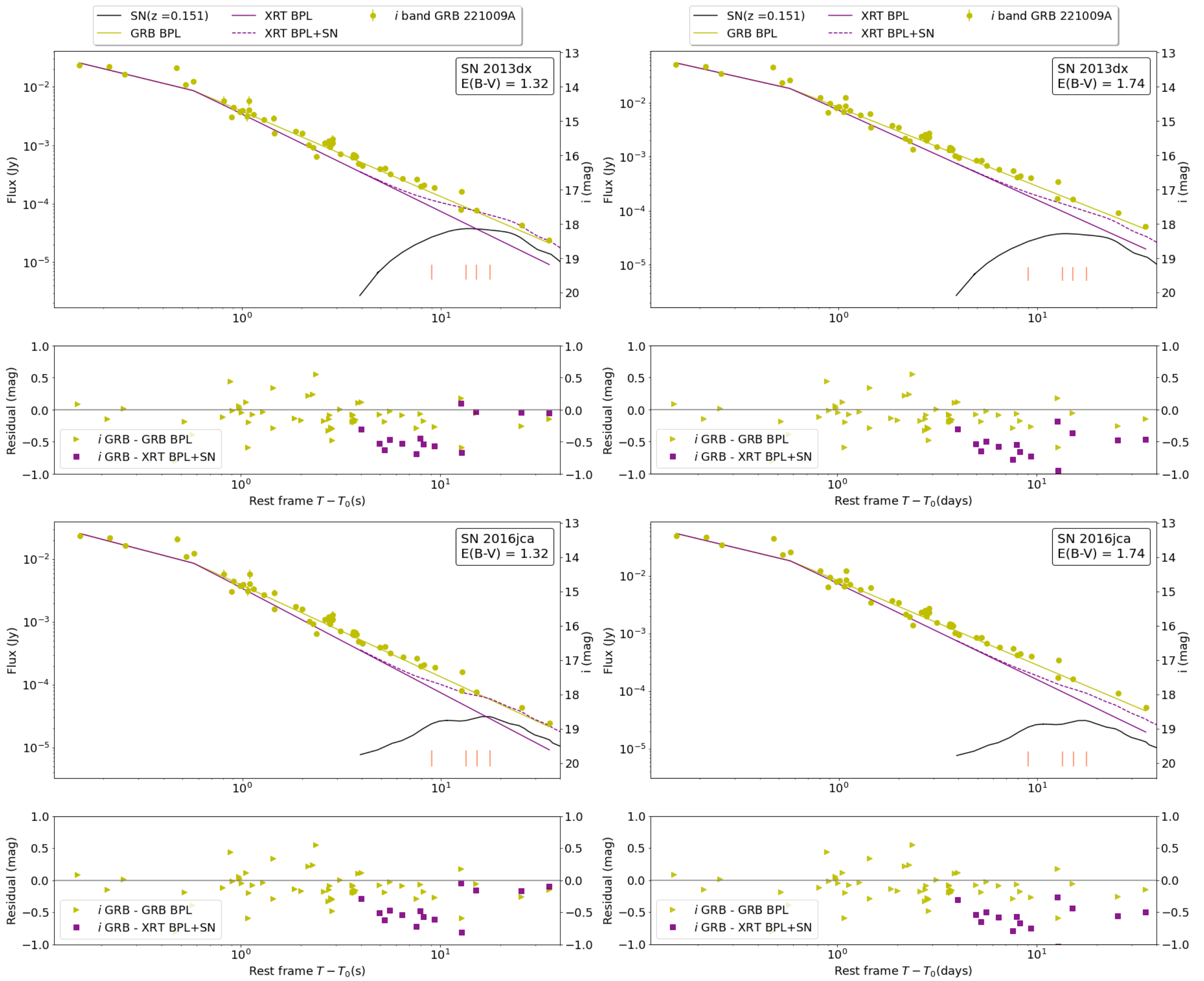

Figure 4. Same plot as Fig. 3 for i filter. The yellow triangle points are the difference between the observed GRB magnitude and broken-power-law estimate. The residual plot shows that the broken power-law fit to the GRB optical data is the best fit for the observed data.

does not find a supernova bump in the light curve, as would be expected for a GRB with a supernova component, though we are unable to exclude the presence of a faint supernova for a high extinction case. In addition, we obtained spectroscopic observations from the HET and MMT. The spectra do not contain clear broad line features indicating associated SN Ic-BL. We summarize the results below:

1. We investigate if the optical light curves contain contributions from the GRB afterglow and a possible supernova. We fit the light curves with two different models. The first model fixes the afterglow contribution to a broken power law with the same decay rate as the X-ray light curve (assumed to be dominated by the GRB afterglow at all times). The second model is a broken power law with a decay rate fit to match the observed data, which assumes that all of the emission is contributed by the GRB afterglow. We also added a SN component at late times for both cases to check if the observed light curve could be the result of afterglow and SN emission for the first model and if a supernova component would have been identified for the second model.

2. We checked how the light curve would evolve in the presence of two different supernovae at a similar redshift to GRB 221009A. In all cases, we find that the afterglow+supernova model provides

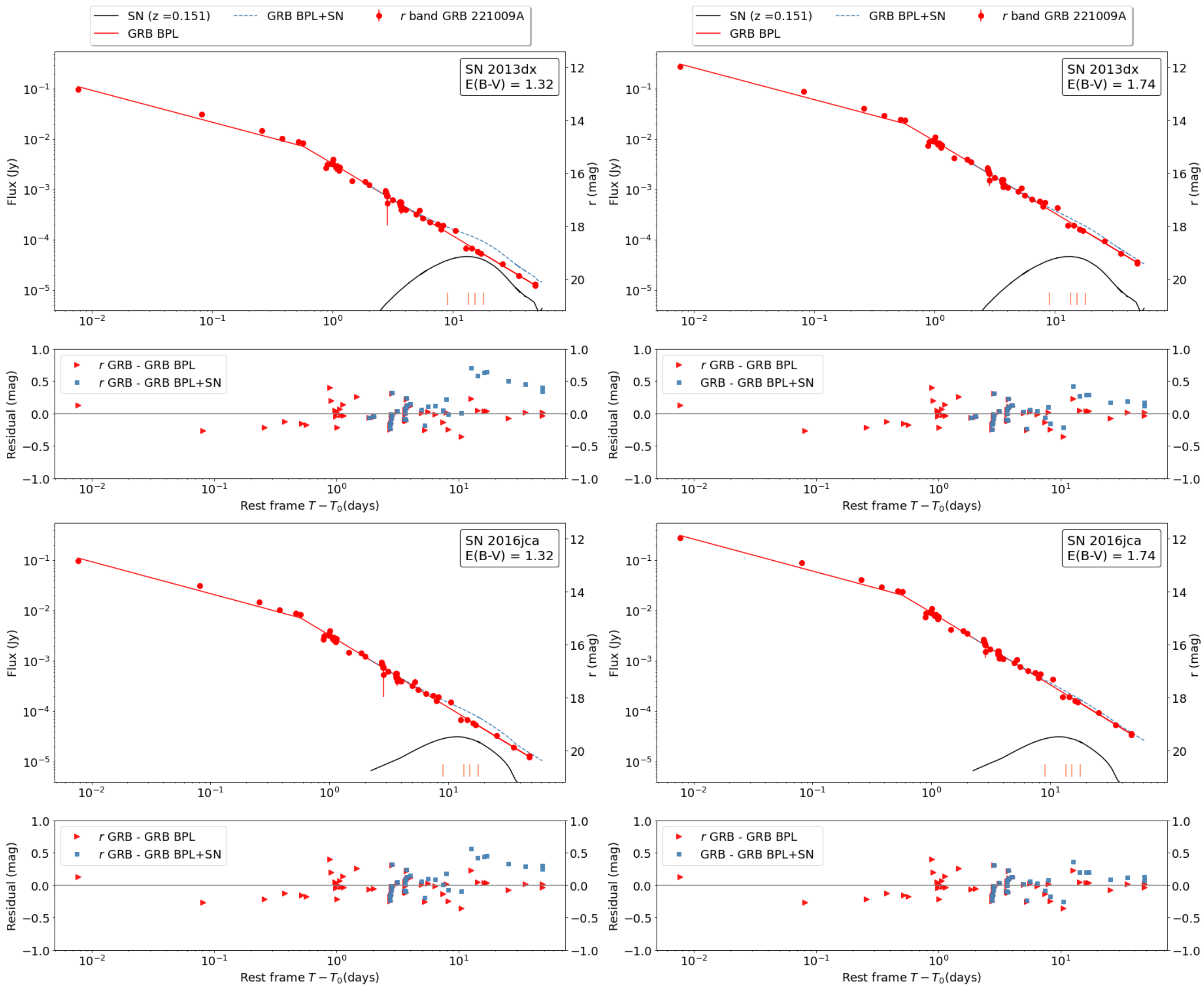

Figure 5. Light curves for the r filter using the two different extinction values of $E(B-V) = 1.32$ mag (left) and $E(B-V) = 1.74$ mag (right). SN 2013dx and SN 2016jca light curves are plotted as black solid lines in top and bottom panels respectively. The sum of SN contribution and GRB afterglow is shown as dashed blue lines. For each case, a residual plot in magnitude is presented. The blue squares are the difference between the supernova contribution plus GRB afterglow estimated by a broken-power-law fit to the optical data. The red triangle points are the difference between the observed GRB magnitude and the broken-power-law estimate.

a worse fit to the data than the afterglow-only model. Thus, we do not find evidence of a bright supernova in our light curve.

3. We observed the spectrum of GRB 221009A to search for spectroscopic signatures of a supernova. We modeled the GRB afterglow contribution to the spectrum as $F_\nu \propto t^{-\alpha}\nu^{-\beta}$. We estimated the value of β using optical photometry. Subtraction of this contribution does not change the features of the spectra. It only brings the flux values closer to zero. We do not detect any consistent, broad features across our spectroscopic sequence. Hence, no clear supernova contribution is detected.

Our study shows that we do not detect a supernova associated with the GRB 221009A. However, we cannot discard the possibility that there could be an associated supernova below our detection limit if we consider the high extinction. The lack of supernova features could be due to the supernova being fainter than SN 2013dx or SN 2016jca (i.e., with an absolute magnitude of $M_r > -19.5$ and $M_i > -19.3$) or due to the high extinction in the direction of GRB 221009A, which could hide the

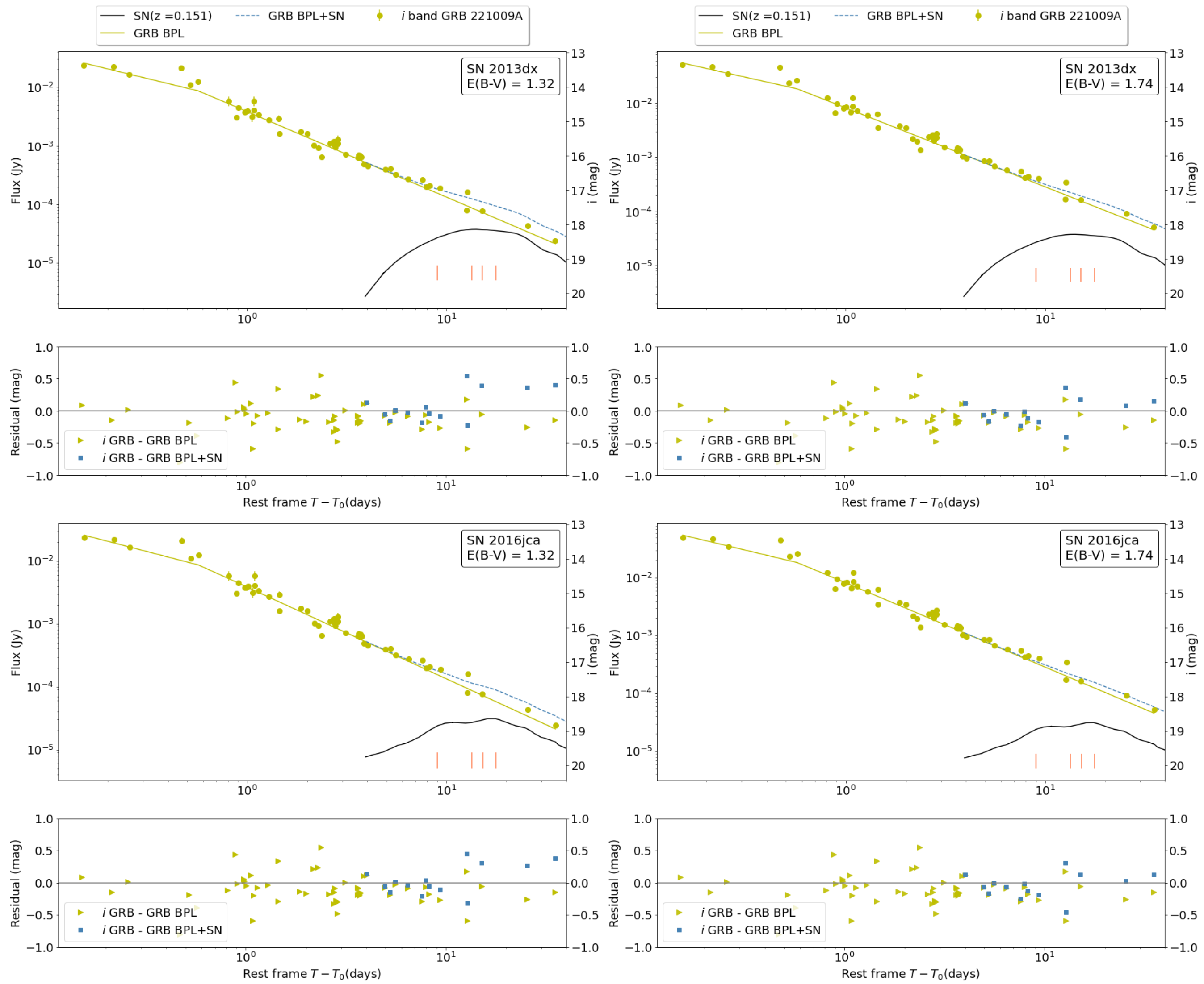

Figure 6. Same plot as Fig. 5 for the i filter. The blue squares are the difference between supernova contribution plus GRB afterglow estimated by broken-power-law fitted to optical data. The yellow triangle points are the difference between the observed GRB magnitude and the broken-power-law estimate.

supernova features. Our non-detection of a supernova from GRB 221009A at this level may suggest that most of the energy produced by the central engine is carried by the relativistic jet, not the bulk ejecta.

We also consider our results in the context of the small but growing sample of GRBs detected at very high gamma-ray energies (TeV). In the case of GRB 190114C, the first GRB with associated TeV photons, an associated supernova was also seen (SN 2019jrj; Melandri et al. 2022). Interestingly, the spectral analysis of Melandri et al. (2022) shows that SN 2019jrj's absorption lines are more similar to those of less luminous CCSNe such as SNe 2004aw (Taubenberger et al. 2006) or 2002ap (Tomita et al. 2006) than to other GRB-SNe. Specifically, SN 2019jrj's emission lines are narrower, meaning that its ejecta was more slowly moving and carried less energy. The photometric analysis of Melandri et al. (2022) shows that the luminosity of SN 2019jrj is lower than SN 2013dx. This luminosity range would be below our detection limit if we assume the extinction to be 1.74 mag for GRB 221009A. In this case, our results suggest the possibility that GRBs capable of accelerating photons to TeV energies are accompanied by underluminous supernovae, possibly providing clues to their central engines and progenitors.

Fulton et al. (2023) reported the detection of a supernova component in their optical light curve of GRB 221009A obtained mainly with Pan-STARRS and

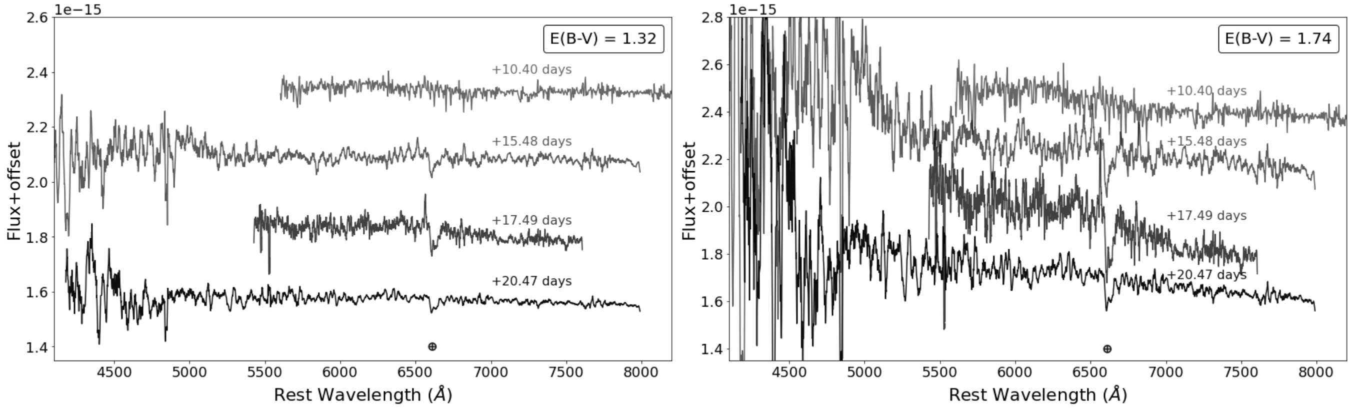

Figure 7. Smoothed spectra of GRB 221009A observed at four different phases of +10.4 (HET), +15.48 (MMT), +17.49 (MMT), and +20.47 (MMT) days after the trigger using two different extinction values of $E(B-V)$=1.32 mag (left) and $E(B-V)$=1.74 mag (right). GRB afterglow contributions have been subtracted from the presented spectra. The wavelengths have been converted to the rest frame assuming a redshift of 0.151. No clear SN Ic-BL features are seen in the spectra.

a few other telescopes. They assume the X-ray decay index as the GRB afterglow decay index and find excess flux in the r, i, and y filters and not in the z filter. They find the excess flux follows a similar behavior to SN 2016jca and SN 2017iuk. Thus, this excess is explained as an emerging supernova with absolute peak AB magnitudes of $M_g = -19.8 \pm 0.6$ mag, $M_r = -19.5 \pm 0.3$, and $M_z = -20.1 \pm 0.3$. Since we do not have good coverage in the z-band light curve and we did not collect any y-band, we have not included these bands in our analyses. Whereas, for r and i filters, we have good coverage of the data set and have done a similar analysis. For our data set, we also find excess in flux when compared to a power-law based on the X-ray data. However, our analyses show that this excess is better explained by a simple broken power-law fit to optical data rather than the addition of a bright supernova component with $M_r = -19.5$ mag. The shallowness in the optical decay can be explained by the relation $\alpha_X = \alpha_{opt} + 0.25$ expected for the slow cooling regime for constant interstellar medium (Zaninoni et al. 2013). If we assume the observed data to be explained by a broken power law with a decay index shallower than the XRT data, and also $E(B-V) = 1.74$ mag, in that case, there could be an associated supernova with $M_r = -19.5$ mag which would not show a clear bump in the r band light-curve.

We note that de Ugarte Postigo et al. (2022) and Rossi et al. (2022a) reported via GCN circulars the detection of associated supernova spectroscopically at an average time of 8 and 8.56 days after the BAT trigger. From our light curve analysis, for us to detect supernova bumps during that time period, the absolute magnitude of the associated supernova would have to be brighter than $M_r = -20.66$ after correcting for the extinction of $E(B-V) = 1.32$ mag. This value is greater than the absolute magnitude at the peak for both SN 1998bw ($M_r = -19.41$) and SN 2012bz ($M_r = -19.63$). We also note that our MMT spectra at the last epoch coincide with the peak in the supernova component from the analyses of Fulton et al. (2023). However, we do not see any broad features in our spectrum (Fig. 7) which is indicative of SN type Ic-BL. We note that our spectrum is noisy compared to other SN spectra as shown in Fig. 8 for comparison.

Alternately, our results could indicate that GRB 221009A has no associated supernova at all. Previously, there have been observations of supernova-less GRBs such as GRB 060505 (Fynbo et al. 2006), GRB 060614 (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006), GRB 111005A (Michałowski et al. 2018), and GRB 2211211A (Rastinejad et al. 2022). For all of these cases, unlike GRB 221009A, the source is not located in a region of high extinction. Thus, dust extinction has been ruled out for the three supernova-less GRBs. For the case of GRB 060614, the afterglow is faint and even a supernova similar to SN 2006aj would be clearly visible in the light curve, ruling out the possibility of even a very faint associated supernova. Dado & Dar (2018) suggest that such supernova-less GRBs could comprise half of the GRB population, and could originate from a phase transition of neutron stars to quark stars in high-mass X-ray binaries.

Recently, the bright GRB 211211A with redshift ($z = 0.0763 \pm 0.0002$) was also found to have no associated supernova (Rastinejad et al. 2022; Troja et al. 2022). Instead, its light curve shows an excess in the NIR which points toward an associated kilonova and a binary neutron star merger origin. In the case of GRB 221009A, we do not detect a strong infrared excess indicative of

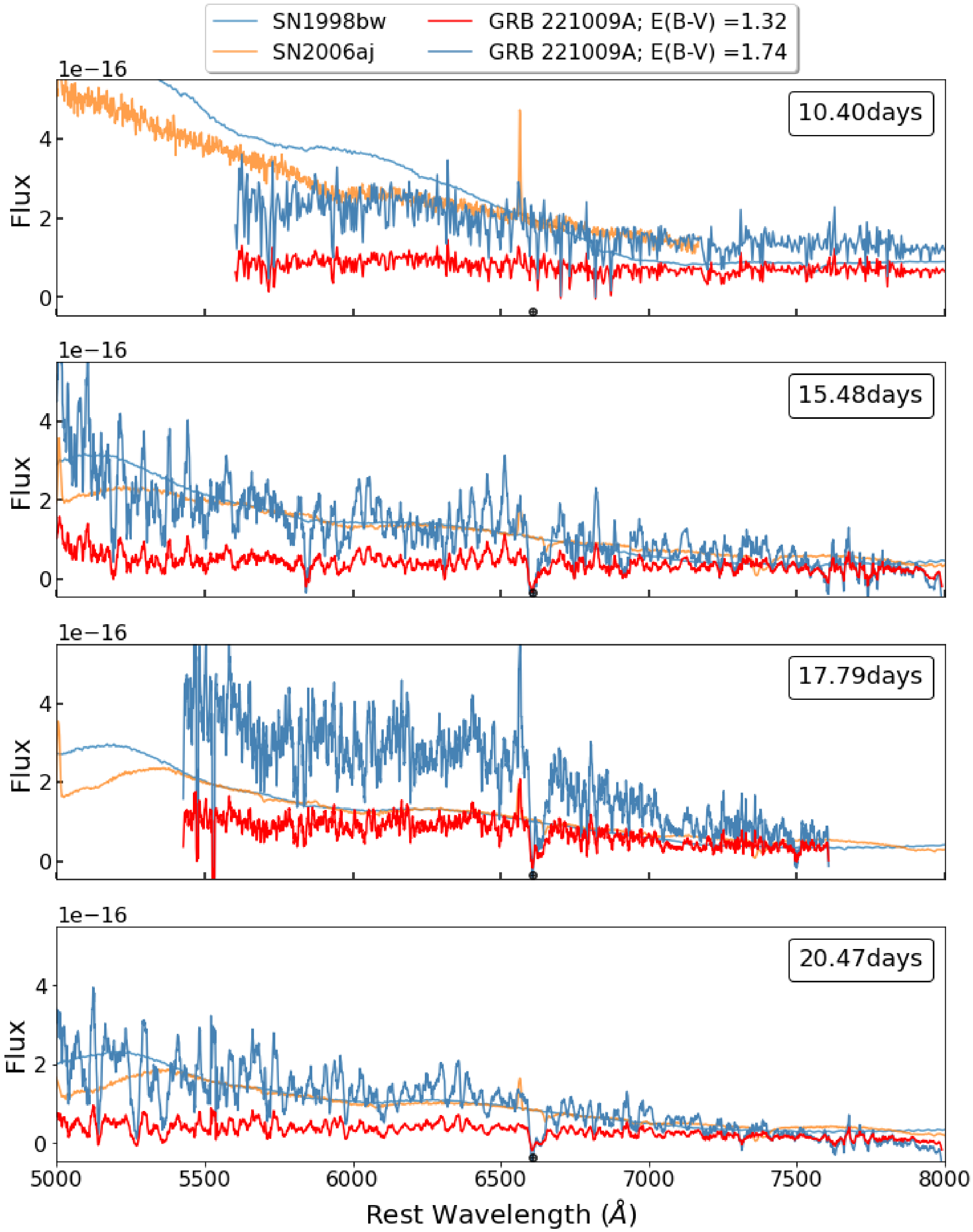

Figure 8. Smoothed spectra of GRB 221009A compared to two supernovae, SN 1998bw and SN 2006aj, which were both associated with GRBs. The spectra have been corrected for extinction using the two values used throughout this work ($E(B-V)$=1.32 mag and $E(B-V)$=1.74 mag) and have been corrected for their redshift appropriately. All the spectra are calibrated to the photometry of GRB 221009A at the same phase and the GRB afterglow contribution is subtracted. The four panels are for four different times since the GRB trigger time: 10.40 days, 15.48 days, 17.49 days, and 20.47 days. The spectrum of GRB 221009A at 10.40 days is from HET, and the spectra at 15.48 days, 17.49 days, and 20.47 days are from the MMT. Although the initial HET spectrum bears some resemblance to SN 1998bw in the high extinction scenario, overall there are no clear supernova features present.

an associated kilonova and thus consider a compact object merger scenario unlikely for this burst. Long-term monitoring of GRB 221009A, including with powerful facilities like HST and JWST, will improve our understanding of the afterglow model and improve our limits on a possible supernova contribution, providing new tests of these and other models for the progenitors and central engines powering the most energetic GRBs.

Facilities: ADS, CTIO:DECam, LBT (MODS), MMT (Binospec), HET (LRS2), Las Cumbres Observatory (MUSCAT3), NED, SOAR (GHTS), WISeREP, HST, IRSA

Software: astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018), Photutils (Bradley et al. 2019), Binospec IDL (Kansky et al. 2019), Panacea, BANZAI (McCully et al. 2018), Light Curve Fitting (Hosseinzadeh & Gomez 2020), MatPLOTLIB (Hunter 2007), NumPy (Harris et al. 2020), Scipy (Virtanen et al. 2020), IRAF (Tody 1986, 1993)

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