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GRB 120422A/SN 2012bz: Bridging the Gap between Low- And High-Luminosity GRBs

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ABSTRACT

At low redshift, a handful of gamma-ray bursts (GRBs) have been discovered with peak luminosities ($L_{\rm iso} < 10^{48.5}$ erg s^{-1}) substantially lower than the average of the more distant ones ($L_{\rm iso} > 10^{49.5}$ erg s^{-1}). The properties of several low-luminosity (low-L) GRBs indicate that they can be due to shock break-out, as opposed to the emission from ultrarelativistic jets. Owing to this, it is highly debated how both populations are connected, and whether there is a continuum between them. The burst at redshift $z = 0.283$ from 2012 April 22 is one of the very few examples of intermediate-L GRBs with a γ-ray luminosity of $L \sim 10^{48.9}$ erg s^{-1} that have been detected up to now. Together with the robust detection of its accompanying supernova SN 2012bz, it has the potential to answer important questions on the origin of low- and high-L GRBs and the GRB-SN connection. We carried out a spectroscopy campaign using medium- and low-resolution spectrographs at 6–10-m class telescopes, covering the time span of 37.3 days, and a multi-wavelength imaging campaign from radio to X-ray energies over a duration of ~ 270 days. Furthermore, we used a tuneable filter centred at Hα to map star formation in the host galaxy and the surrounding galaxies. We used these data to extract and model the properties of different radiation components and incorporate spectral-energy-distribution fitting techniques to extract the properties of the host galaxy. Modelling the light curve and spectral energy distribution from the radio to the X-rays revealed the blast-wave to expand with an initial Lorentz factor of $\Gamma_0 \sim 60$, low for a high-L GRB, and that the afterglow had an exceptional low peak luminosity-density of $\lesssim 2 \times 10^{30}$ erg s^{-1} Hz^{-1} in the sub-mm. Because of the weak afterglow component, we were for the first time able to recover the signature of a shock break-out that was not a genuine low-L GRB. At 1.4 hours after the burst, the stellar envelope had a blackbody temperature of $k_{\rm B}T \sim 16$ eV and a radius of $\sim 7 \times 10^{13}$ cm. The accompanying SN 2012bz reached a peak luminosity of $M_{\rm V} = -19.7$ mag, 0.3 mag more luminous than SN 1998bw. The synthesised nickel mass of 0.58 M$_\odot$, ejecta mass of 5.87 M$_\odot$, and kinetic energy of 4.10×10^{52} erg were among the highest recorded values for GRB-SNe, making it the most luminous spectroscopically confirmed SN to data. Nebular emission lines at the GRB location were visible, extending from the galaxy nucleus to the explosion site. The host and the explosion site had close to solar metallicities. The burst occurred in an isolated star-forming region with a SFR that is 1/10th of that in the galaxy's nucleus. While the prompt γ-ray emission points to a high-L GRB, the weak afterglow and the low Γ_0 were very atypical for such a burst. Moreover the detection of the shock-break-out signature is a new quality for high-L GRBs. So far, shock break-outs were exclusively detected for low-L GRBs, while GRB 120422A had an intermediate $L_{\rm iso}$ of $\sim 10^{48.9}$ erg s^{-1}. Therefore, we conclude that GRB 120422A was a transition object between low- and high-L GRBs, supporting the failed-jet model that connects shock-break-out driven low-L and high-L GRBs that are powered by ultra-relativistic jets.

Key words. dust, extinction gamma rays: bursts : individual: GRB 120422A - supernovae: individual: SN 2012bz

1. Introduction

The discovery of SN 1998bw in the error-box of GRB 980425 by Galama et al. (1998) gave the study of the GRB-SN connection a flying start. This event remains unique in several ways among the many hundred GRBs that have been studied since. It is still the nearest GRB with a measured redshift and it is the least energetic GRB yet observed. Nevertheless, SN 1998bw seems to be representative of the type of SNe that accompany the more typical and brighter long-duration GRBs (for recent reviews see Woosley & Bloom 2006; Hjorth & Bloom 2012), i.e. a bright ($M_{\rm bol,\,peak} \lesssim -19$ mag), broad-lined (due to the expansion velocities of several 10^4 km s^{-1}) type Ic SN (i.e. lacking of hydrogen and helium). Interestingly, in only two out of 16 cases of nearby long-duration GRBs ($z < 0.5$) no SN was found to deep limits (Fynbo et al. 2006; Della Valle et al. 2006a; Gal-Yam et al. 2006; Ofek et al. 2007; Kann et al.

2011), though their classification is not free of ambiguity (e.g. Zhang et al. 2009; Kann et al. 2011).

So far, most GRBs with spectroscopically-confirmed SN associations have had a much lower apparent luminosity than the bulk of the long-duration GRBs. GRB 030329 was the first example of a high-luminosity GRB ($\log L_{\rm iso}/\left({\rm erg\,s^{-1}}\right) = 50.9$) that was accompanied by a SN (Hjorth et al. 2003; Matheson et al. 2003; Stanek et al. 2003). However, there is a growing number of high-luminosity bursts, defined by $\log L_{\rm iso}/\left({\rm erg\,s^{-1}}\right) > 49.5$ (Hjorth 2013), with a spectroscopically-confirmed SN, such as GRBs 050525A (Della Valle et al. 2006b), 081007 (Della Valle et al. 2008; Jin et al. 2013), 091127 (Cobb et al. 2010; Berger et al. 2011), 101219B (Sparre et al. 2011), 130215A (de Ugarte Postigo et al. 2013), 130427A (Xu et al. 2013; Levan et al. 2013), and 130831A (Klose et al. 2013).

Bromberg et al. (2011) suggested that low-luminosity GRBs ($\log L_{\rm iso}/\left({\rm erg\,s^{-1}}\right) < 48.5$; Hjorth 2013) are driven by high-energy emission associated with the shock breakout of their progenitor stars rather than an emerging jet as in typical high-luminosity GRBs (Colgate & McKee 1969; Kulkarni et al. 1998; Campana et al. 2006; Soderberg et al. 2006a; Nakar & Sari 2012). A consequence of these different energy sources is that low-L GRBs seem to be about 10-1000 times more common than high-L GRBs (Pian et al. 2006; Guetta & Della Valle 2007; Virgili et al. 2009; Wanderman & Piran 2010), but because of their low luminosities they are primarily found at low redshifts as rare events (one every ~ 3 years). In contrast to high-L GRBs, low-L GRBs typically have single-peak high-energy prompt light curves and can have soft high-energy spectra with peak energies below ~ 50 keV (Campana et al. 2006; Starling et al. 2011, but see Kaneko et al. 2007). Their optical emission is dominated by the SN emission. Until now, radio and X-ray afterglows, but no optical afterglows have been detected for them. The recent GRB 120422A is a particularly interesting case. It has a γ-ray luminosity that is intermediate between low- and high-luminosity GRBs and has a robust detection of the associated SN (Malesani et al. 2012a; Sánchez-Ramírez et al. 2012; Wiersema et al. 2012; Melandri et al. 2012). A study of this event may thus answer important questions about the origin of both high- and low-L GRBs.

The paper is structured as follows. We describe the data gathering and outline the data analysis in Sect. 2, and present the results on the transient following the GRB, from radio to X-ray wavelengths, and the accompanying GRB-SN, SN 2012bz, in Sect. 3, and the properties of the GRB environment and the host galaxy in 4. In Sect. 5 we compare our findings to other events and argue that GRB 120422A represents the *missing link between low- and high-L GRBs*. Finally, we summarise our findings and present our conclusions in Sect. 6.

Throughout the paper we use the convention for the flux density $F_\nu\left(t\right) \propto t^{-\alpha}\nu^{-\beta}$, where α is the temporal slope and β is the spectral slope. We refer to the solar abundance compiled in Asplund et al. (2009) and adopt ${\rm cm}^{-2}$ as the linear unit of column densities, N. Magnitudes reported in the paper are given in the AB system and uncertainties are given at 1σ confidence level (c.l.). We assume a ΛCDM cosmology with $H_0 = 71~{\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\rm m} = 0.27$, and $\Omega_\Lambda = 0.73$ (Larson et al. 2011).

2. Observations and data reduction

On 2012 April 22 at 7:12:49 UTC (hereafter called T_0; MJD = 56039.30057), the Burst Alert Telescope (BAT, Barthelmy et al. 2005) aboard *Swift* detected and localised a faint burst (Troja et al. 2012). Its γ-ray light curve comprised a single peak with a duration of $T_{90} = 5.4 \pm 1.4$ s, followed by a fainter and lower-energetic emission beginning 45 s after the trigger and lasting for 20 s. Within 86 s, the *Swift* X-Ray Telescope XRT (Burrows et al. 2005) and the UV/Optical Telescope UVOT (Roming et al. 2005) started to observe the field and detected an uncatalogued and rapidly decaying source at R.A., Dec. (J2000) = $09^{\rm h}07^{\rm m}38^{\rm s}\!.42\,(\pm0.01), +14^\circ01'07''\!.1\,(\pm0.2)$ (Beardmore et al. 2012; Kuin & Troja 2012; Zauderer et al. 2012). Only $2''$ NE of the explosion site there is a SDSS galaxy (Cucchiara et al. 2012; Tanvir et al. 2012). Spectra of the explosion site revealed several absorption and emission lines at a common redshift of $z = 0.283$, and a large number of emission lines at the location of the SDSS galaxy at a redshift identical to that of the GRB (Schulze et al. 2012b; Tanvir et al. 2012).

Thanks to its low redshift and its γ-ray luminosity ($E_{\rm iso} \sim 4.5 \times 10^{49}$ erg and $L_{\rm iso} \sim 10^{49}$ ${\rm erg\,s^{-1}}$; Zhang et al. 2012) being in between that of high- and low-L GRBs, it is an ideal target to search for the accompanying GRB-SN, or place stringent constraints on its absence, if it is another example of a SN-less long GRB. We therefore triggered an extensive imaging campaign with several telescopes from mm to optical wavelengths, as well as a large low- and medium-resolution spectroscopy campaign carried out at 6-m to 10-m class telescopes. These campaigns began ~ 31 min after the trigger and ended ~ 44.6 days later. Furthermore, we obtained an X-ray spectrum with *XMM-Newton* 12 days after the explosion. In addition to our own efforts, the GRB-dedicated satellite *Swift* observed the GRB at UV/optical and X-ray wavelengths for 54.3 days. We incorporated these data as well as radio data obtained with the Arcminute Microkelvin Imager Large Array (AMI-LA; Staley et al. 2013) to present a comprehensive study of this event. In the following, we briefly summarise the observations and describe how the data were analysed. A log of our observations is presented in Tables 1, 2, A.1, and B.1.

2.1. Optical and NIR spectroscopy

Our spectroscopic campaign began 51 min after the trigger and covered a time span of 37.7 days. The spectral sequence comprised seven medium-resolution spectra obtained with VLT/X-shooter (Vernet et al. 2011); the first three spectra were obtained covering the full spectral bandwidth from 3000 to 24800 Å, while for the remaining ones a K-blocking filter (cutting the wavelength coverage at 20700 Å; Vernet et al. 2011) was adopted to increase the S/N in the H band. These observations were complemented with ten low-resolution spectra acquired with the Gemini Multi-Object Spectrograph (GMOS, Hook et al. 2004), mounted on Gemini-North and -South, the Gran Telescopio Canarias (GTC) OSIRIS camera, the Keck Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) and the Magellan Low Dispersion Survey Spectrograph 3 (LDSS3). Table 1 summarises these observations.

Observing conditions were not always photometric, and observations were performed irrespective of moon distance

Table 1. Summary of spectroscopic observations

MJD (days)	Epoch (days)	Telescope/Instrument	Arm/Grating	Spectral range (Å)	Resolving power	Exposure time (s)	Slit width	Position angle
56039.345	0.0443	Gemini/GMOS-N	R400+OG515	5942–10000	960	2 × 900	1″.0	180°.0
56039.431	0.1301	Gemini/GMOS-N	B600	3868–6632	844	2 × 400	1″.0	180°.0
56040.017	0.7160	VLT/X-shooter	UVB VIS NIR	3000–5500 5500–10000 10000–24800	4350 8800 5100	4 × 1200 4 × 1200 16 × 300	1″.0 0″.9 0″.9	41°.0
56042.911	3.6112	GTC/Osiris	R500R	4800–10000	500	4 × 1500	1″.2	100°.0
56044.014	4.7139	VLT/X-shooter	UVB VIS NIR	3000–5500 5500–10000 10000–24800	4350 8800 5100	4 × 1200 4 × 1200 16 × 300	1″.0 0″.9 0″.9	41°.0
56044.257	4.9565	Keck/LRIS	400/3400 400/8500	3000–5500 5500–10000	750 1700	2 × 900	0″.7	50°.0
56048.061	8.7604	VLT/X-shooter	UVB VIS NIR	3000–5500 5500–10000 10000–24800	4350 8800 5100	4 × 1200 4 × 1200 16 × 300	1″.0 0″.9 0″.9	41°.0
56048.304	9.0036	Gemini/GMOS-N	R400	4442–8608	960	4 × 1200	1″.0	170°.0
56052.978	13.6772	Gemini/GMOS-S	R400+GG455	4892–9008	960	1 × 2400	1″.0	180°.0
56053.930	14.6301	GTC/Osiris	R500R	4800–10000	500	3 × 1200	1″.2	75°.0
56057.996	18.6962	VLT/X-shooter[a]	UVB VIS NIR	3000–5500 5500–10000 10000–20700	4350 8800 5100	4 × 1200 4 × 1200 16 × 300	1″.0 0″.9 0″.9	52°.0
56061.996	22.6953	Gemini/GMOS-S	R400+GG455	4892–9108	960	2 × 2400	1″.0	-30°.0
56063.999	24.6992	VLT/X-shooter[a]	UVB VIS NIR	3000–5500 5500–10000 10000–20700	4350 8800 5100	4 × 1200 4 × 1200 16 × 300	1″.0 0″.9 0″.9	52°.0
56066.068	26.7680	Magellan/LDSS3	VPH_ALL	3700–9400	800	1 × 1400	1″.2	141°.0
56076.025	36.7250	VLT/X-shooter[a]	UVB VIS NIR	3000–5500 5500–10000 10000–20700	4350 8800 5100	4 × 1200 4 × 1200 16 × 300	1″.0 0″.9 0″.9	-143°.9
56077.000	37.7001	VLT/X-shooter[a]	UVB VIS NIR	3000–5500 5500–10000 10000–20700	4350 8800 5100	4 × 1200 4 × 1200 16 × 300	1″.0 0″.9 0″.9	151°.1

Notes. Column "Epoch" shows the logarithmic mean-time after the burst in the observer frame. Resolving powers and spectral ranges are the nominal values from instrument manuals. [(a)] The K-band blocking filter was used to increase the S/N in JH band.

and phase. For each epoch, we centred the slit on the explosion site and in some cases varied the position angle to probe different parts of the host galaxy, as illustrated in Fig. 1.

VLT/X-shooter data were reduced with the X-shooter pipeline v2.0 (Goldoni et al. 2006).[1] To extract the one-dimensional spectra of the transient and the host galaxy, we used a customised tool that adopts the optimal extraction algorithm by Horne (1986). The Gemini, GTC, and Magellan spectra were reduced and calibrated using standard procedures in `IRAF` (Tody 1993). Keck data were reduced with a custom pipeline that makes use of standard techniques of long-slit spectroscopy. In all cases we chose a small aperture for studying the optical transient. For studying the emission lines, we extracted the spectral point spread function and extracted the spectrum of the nucleus and the afterglow within an aperture of $1 \times \mathrm{FWHM}$ of each trace, e.g. the FWHMs were 1″.34 and 0″.86 for the galaxy nucleus and the explosion site, respectively, for the UVB and VIS of the first X-shooter spectrum.

All spectra were flux-calibrated with corresponding spectrophotometric standard star observations and the absolute flux scale was adjusted by comparing to photometry. The data were corrected for the Galactic reddening of $E(B-V) = 0.04$ mag (Schlegel et al. 1998). All wavelengths were transformed to vacuum wavelengths. In addition, X-shooter data were corrected for heliocentric motion. No telluric correction was applied, as it has no implications for our analysis.

[1] http://www.eso.org/sci/software/pipelines/

Table 2. Summary of mm and sub-mm observations

MJD (days)	Epoch (days)	Instrument	Frequency	Exposure time (s)	F_ν (mJy; 3σ)
56039.3291	0.0537	SCUBA-2	350 GHz	5639	< 7.20
56039.3291	0.0537	SCUBA-2	665 GHz	5639	< 225
56039.5676	0.2670	AMI-LA[a]	15 GHz		< 0.62
56040.1923	0.8917	SMA	272 GHz	3420	< 3.60
56041.6806	2.3800	AMI-LA[a]	15 GHz		< 0.47
56041.9422	2.6416	PdBI	86.7 GHz	5040	< 0.39
56041.9943	2.6937	CARMA	92.5 GHz	3480	< 1.15
56043.6806	4.3800	AMI-LA[a]	15 GHz		< 0.37
56046.7206	7.4200	AMI-LA[a]	15 GHz		< 0.24
56048.8054	9.5048	PdBI	86.7 GHz	5040	< 0.24
56052.7506	13.450	AMI-LA[a]	15 GHz		< 0.23
56067.8906	28.590	AMI-LA[a]	15 GHz		< 0.46

Notes. Column "Epoch" shows the logarithmic mean-time after the burst in the observer frame. [(a)] Data taken from Staley et al. (2013).

2.2. Imaging

Following the BAT trigger, *Swift* slewed immediately to the burst and UVOT took a v-band settling exposure 86 s after the BAT trigger. Science observations began at $T_0 + 104$ s and cycled through all filters. Follow-up observations in the v and b bands continued until $T_0 + 2.3$ days, in the $uvw1$, $uvm2$ and $uvw2$ UV filters until $T_0 + 9.7$ days, and in the u band until $T_0 + 54.3$ days, at which time a final set of observations of the host galaxy was taken in all filters.[2]

Our ground-based imaging campaign began 31 min after the explosion and spanned a time interval of ~ 45 days. Due to the proximity of a $R = 8.24$ mag star (79″ NW of the explosion site), we either moved the position of the optical transient to the NW corner of the chip, or (most of the time) obtained short dithered exposures to avoid excessive saturation.

Observations were carried out with the 2.56-m Nordic Optical Telescope (NOT) equipped with ALFOSC, MOSCA, and StanCAM in the $u'g'Rr'Ii'$ bands (Malesani et al. 2012b; Schulze et al. 2012a). These observations began at 14.29 hr post-burst and were stopped at 44.5 days because of the small Sun distance. Further imaging data were acquired with GMOS-N and GMOS-S in the $u'g'r'i'z'$ bands between 31 min and 40.7 days after the explosion (Cucchiara et al. 2012; Perley et al. 2012a). The Gamma-ray Optical/Near-infrared Detector (GROND, Greiner et al. 2007, 2008) mounted at the MPG/ESO 2.2 m telescope on La Silla imaged the field simultaneously in four optical ($g'r'i'z'$) and three NIR (JHK_s) bands starting at $T_0 + 16.5$ hr (Nardini et al. 2012). Additional epochs were obtained at nights 2, 9, 11, 20, 29, before the visibility of the field was compromised by its small Sun distance on day 39. We monitored the optical transient in the $g'r'i'$ bands with the 60-inch Palomar telescope for 37 days beginning at $T_0 + 0.87$ day and in the JHK bands with the Wide Field Camera (WFCAM) mounted at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea at seven epochs between $T_0 + 0.06$ and 25.98 day.

We complemented these optical observations with the 10.4-m GTC telescope equipped with OSIRIS in the $g'r'i'z'$ bands, the multi-filter imager BUSCA mounted at the 2.2-m telescope of Calar Alto (CAHA) in g' and the r' bands,[3] the 3.5-m CAHA telescope equipped with the Omega$_{2000}$ camera in the z' band,[4] the LDSS3 camera mounted at the 6-m Clay telescope telescope in the r' and i' bands, the Direct CCD Camera mounted on the Irenee du Pont 2.5-m telescope at Las Campanas in the r' and i' bands, the 2.4-m Gao-Mei-Gu (GMG) telescope in i', and the 1.04-m and the 2-m optical-infrared Himalayan Chandra Telescope in R_c and I_c. Additional NIR data were acquired with the Omega$_{2000}$ in the $YJHK_s$ bands, the Near-Infrared Imager (NIRI) mounted on Gemini-North in the J and K bands, and the Wide-field Infrared Camera (WIRC) on the 200-inch Hale telescope at Palomar Observatory in the J band (Perley et al. 2012b).

Very late-time observations were secured with the 2.0-m Liverpool telescope, with BUSCA mounted at the 2.2-m CAHA, and GMOS mounted at Gemini-North (Table B.1). The observation with the Liverpool telescope comprises 185 images. To minimise the data heterogeneity an observational seeing constraint of $< 1''.1$ was imposed for all epochs.

[2] Additional UVOT data were acquired in October 2012. These data are not discussed in this paper. This has no implications on our work.

[3] http://www.caha.es/newsletter/news01a/busca/

[4] http://www.mpia-hd.mpg.de/IRCAM/O2000/

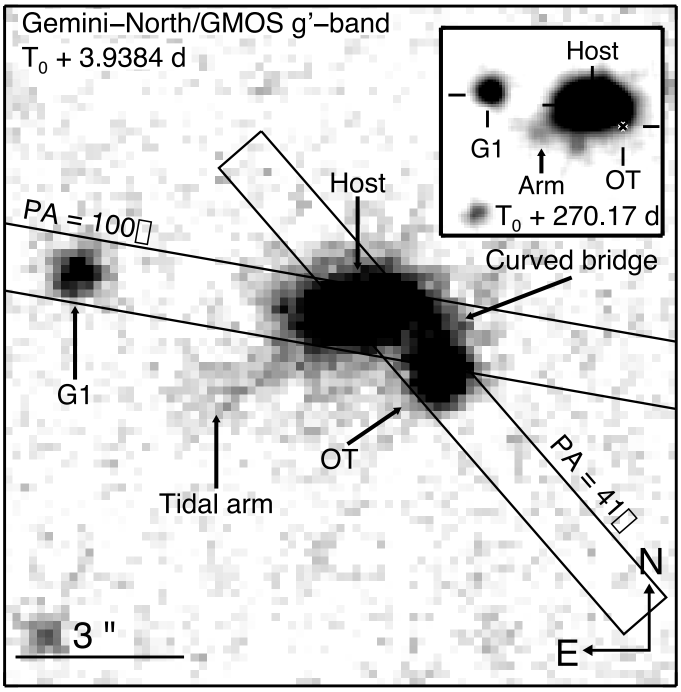

Fig. 1. Field of GRB 120422A (12″ × 12″). The position of the optical transient (OT) accompanying GRB 120422A is marked, as well as of the host galaxy and the curved bridge of emission connecting the explosion site with the host's nucleus. Galaxy G1 has the same redshift as the GRB. The projected distance between the explosion site and the galaxy G1 is 28.7 kpc. The inset shows the field observed in the g'-band with GMOS-N at 270.2 days after the burst. The image cuts were optimised to increase the visibility of the tidal arm that partly connects the host galaxy and G1. The most important slit orientations of our spectroscopic campaign (Table 1) are overlaid.

The CAHA observation did unfortunately not go very deep. We will not discuss these data in the following.

In addition to these broad-band observations, we made use of the tuneable filters at the 10.4-m GTC to trace the Hα emission in the host galaxy on 2012 May 16, 25.5 days after the burst. Observations consisted of 5×600 s exposures using a 15-Å wide filter tuned to the wavelength of Hα at the redshift of the burst ($\lambda_{\rm obs} = 8420$ Å), and a 3×100 s exposure with a 513-Å-wide order-sorter filter centred at 8020 Å to probe the continuum emission (filter f802/51). The seeing was $\sim 1''$, although the transparency was affected by extinction due to Saharan dust suspended in the atmosphere (Calima).

In general, observing conditions were not always photometric; in particular, part of the NOT observations suffered from poor transparency due to the Calima. Table A.1 summarises all observations with good data quality.

We obtained the UVOT data from the *Swift* Data Archive.[5] These data had bad pixels identified, mod-8 noise corrected, and endowed with FK5 coordinates. We used the standard UVOT data analysis software distributed with `HEASOFT 6.12` along with the standard calibration data.[6] Optical and NIR data were processed through standard

[5] http://www.swift.ac.uk/swift_portal/

[6] http://heasarc.nasa.gov/lheasoft/

procedures (bias subtraction and flat field normalisation) using `IRAF` or instrument specific software packages, i.e. the `GEMINI IRAF` software package for GMOS and NIRI, for GROND data a customised pipeline (for details we refer to Yoldaş et al. 2008 and Krühler et al. 2008), a modified version of the `WIRCSoft` package for P200/WIRC data,[7] and for WFCAM data the UKIRT pipeline.[8] Some observations suffered from variable conditions, and in those cases individual images were weighted according to their S/N. The i'- and the z'-band images suffer from fringing, which was corrected using a fringe pattern computed from the science data themselves, although in some cases the presence of the halo from the nearby bright star hampered the process. These data resulted in a lower S/N. Astrometric calibration was computed against the USNO-B1 catalog (Monet et al. 2003), yielding an *rms* of 0.″4. All images were then registered together, yielding a relative RMS of less than 0.″08. We measure the afterglow location to be R.A., Dec. (J2000) = $09^{h}07^{m}38^{s}42, +14^{\circ}01'07''5$.

2.2.1. Sub-mm/mm observations

Our sub-mm/mm observations comprised five epochs and cover a time interval of 9.48 days. First, Smith et al. (2012) simultaneously obtained an early epoch at 450 μm and 850 μm with the sub-millimetre continuum camera SCUBA-2 (Holland et al. 2013) on the James Clerk Maxwell Telescope (JCMT). The 1.6-hr observation began at T_0 + 41.5 min and was performed under moderate weather conditions. The CSO 225 GHz tau, which measures the zenith atmospheric attenuation, was 0.089 initially, but generally degraded through the run. The elevation of GRB 120422A fell from 54.°6 to 30.°4. In the consecutive night, Martin et al. (2012) triggered a short 45-min snapshot observation at the Submillimeter Array (SMA) at T_0+21.4 hr. Receivers were tuned to the local oscillator (LO) centre frequency of 271.8 GHz (λ = 1.1 mm), with the correlator configured to cover two 4 GHz bands centred at ±6 GHz from the LO frequency. All 8 SMA antennas were used in its very extended configuration under excellent weather conditions, with an average zenith opacity of 0.03 (precipitable water vapour of PWV $\sim$ 0.5 mm) at 225 GHz. A further observation was carried out by Perley (2012) with the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) in D-configuration at 92.5 GHz (λ = 3 mm). This observation was carried out between 23:13 UT on 24 April and 00:29 UT on April 25. The total on-source integration time was 58 min. We finally obtained two epochs with the Plateau de Bure Interferometer (PdBI) at a frequency of 86.7 GHz (λ = 3.4 mm) in its 6 antenna compact D configuration. These observations began at T_0 + 2.6416 and 9.5048 days and lasted for 84 min each. AMI-LA obtained six epochs between 0.27 and 28.59 days after the burst (Staley et al. 2013).

The SCUBA-2 data were reduced in the standard manner (Chapin et al. 2013) using `SMURF` (Version 1.5.0) and `KAPPA` (Version 2.1-4) from the Starlink Project.[9] Observations of the SCUBA-2 calibrator Mars bracketed the GRB 120422A observation, and observations of the calibrator CRL2688 were taken several hours later. The calibration observations spanned a larger range of weather conditions than during the GRB 120422A run, and were in general agreement with the standard values of the flux conversion factors (Dempsey et al. 2013), which were then used for the flux normalisation. We reduced CARMA and SMA data with the `MIRIAD` and `MIR-IDL` software packages (Sault et al. 1995).[10] CARMA data were absolute flux calibrated with observations of 3C84 and Mars. The calibration of the SMA data is twofold: first we used the nearby quasars J0854+201 and J0909+013 as atmospheric gain calibrators, and then J0854+201 for bandpass calibration. Absolute flux calibration was bootstrapped from previous measurements of these quasars resulting in an absolute flux uncertainty of $\sim$ 30%. PdBI data were reduced with the standard `CLIC` and `MAPPING` software distributed by the Grenoble GILDAS group.[11] The flux calibration was secured with the Be binary star system MWC349 (F_ν = 1.1 Jy at 86.7 GHz).

2.2.2. X-ray observations

Swift/XRT started to observe the BAT GRB error circle roughly 90 s after the trigger, while it was still slewing. Observations were first carried out in windowed timing mode for 80 s. When the count rate was $\lesssim$ 1 ct s^{-1}, XRT switched to photon counting mode. Observations continued until $T_0 + 53.8$ days, when the visibility of the field was compromised by its small Sun distance. We obtained the temporal and spectroscopic data from the *Swift*/XRT Light Curve and Spectrum Repository (Evans et al. 2007, 2009). GRB 120422A was also observed by *XMM-Newton* with a DDT, starting at 2012 May 3, 15:13 UT. At this epoch, exposures of 56841, 58421 and 58426 s were obtained with the PN, MOS1 and MOS2 detectors, respectively.

To analyse the spectroscopic data we used `Xspec`, version 12.7.1, as part of `HeaSoft` 6.12, *XMM-Newton* specific calibration files and for the *Swift*/XRT pc mode data the respective *Swift* calibration files version 13. The X-ray emission up to $T_0 + 200$ s was discussed in detail in Starling et al. (2012) and Zhang et al. (2012). Therefore, we focus on the analysis of the data after that epoch. In total, XRT registered 270 background-subtracted photons between 0.3 and 10 keV; data that were flagged as bad were excluded from analysis. We re-binned the spectrum to have at least 20 count per bin and applied χ^2 statistics.

2.3. Photometry

Measuring the brightness of the transient is complicated due to blending with its extended, offset host galaxy. To limit the host contribution to the transient photometry, we used point-spread function (PSF) fitting techniques. Using bright field stars, a model of the PSF was constructed for each individual image and fitted to the optical transient. To provide reliable fit results, all images were registered astrometrically to a precision of better than 0.″08, and the centroid of the fitted PSF was held fixed with a small margin of re-centering corresponding to the uncertainty of the astrometric alignment of the individual images. In addition, the PSF-fitting radius was adjusted to the specific conditions of the observations and instrument, in particu-

[7] http://humu.ipac.caltech.edu/~jason/sci/wircsoft/index.html
[8] http://casu.ast.cam.ac.uk/surveys-projects/wfcam
[9] http://starlink.jach.hawaii.edu/starlink
[10] http://www.atnf.csiro.au/computing/software/miriad/ https://www.cfa.harvard.edu/~cqi/mircook.html
[11] http://www.iram.fr/IRAMFR/GILDAS

lar seeing and pixel scale. The fit radius is different for each observation, but typically in the range between 0.″5 and 0.″8. Generally, the radius was smaller under unfavourable sky conditions in an attempt to minimise the host's effect on the fit. Naturally, this leads to a lower S/N for these measurements than one would expect for isolated point sources.

For images taken under adverse sky conditions (seeing $\gtrsim$ 1.″6), with imagers with large pixel scales (e.g. the NIR channels of GROND with 0.″6 per pixel), or in filters/epochs with low S/N (e.g. most of the late NIR data), the individual contributions of point-source and galaxy cannot be disentangled robustly. These measurements are ignored in the following analysis. For all observations the source was close to the centre of the field of view, and differences in the PSF between observations were, therefore, negligible.

To measure the brightness of the transient in the UVOT images, we measured the host galaxy flux at the position of the SN from the later UVOT observations, where there was no longer a contribution from the GRB or SN. This additional flux was then subtracted from our photometric measurements at the position of the GRB. In contrast, host-galaxy photometry was performed via aperture techniques. Here, we used our PSF-model to subtract the transient from the deepest images in each filter with the clearest separation between galaxy and point source, i.e. those images with the smallest FWHM of the stellar PSF. A circular aperture radius was chosen sufficiently large (2.″5, e.g. 10.7 kpc at $z = 0.2825$), so that the missed emission from low surface brightness regions does not affect our photometry significantly. In addition, we also corroborated the galaxy photometry using elliptical Kron apertures (Kron 1980) via their implementation in `Source Extractor` (Bertin & Arnouts 1996).

Once a magnitude was established, it was calibrated photometrically against the brightness of a number of field stars measured in a similar manner. Photometry was tied to the SDSS DR8 (Aihara et al. 2011) in the optical filters ($u'g'r'i'z'$) and 2MASS (Skrutskie et al. 2006) in the NIR (JHK_s). For those filter bands not covered by our primary calibration systems (e.g. I_C or Y), we used the instrument-specific band passes to transform magnitudes into the respective filter system via synthetic photometry similar to the procedure outlined in Krühler et al. (2011b). UVOT images were calibrated using the method described in Poole et al. (2008).

The photometric error was then estimated based on the contributions from photon statistics and goodness of the PSF fit (typically between 0.5 to 15 %), the absolute accuracy of the primary calibration system ($\approx$ 2–3%), the systematic scatter of different instrument/bandpasses with respect to the primary calibrators ($\approx$ 3–6%) or the uncertainty in the colour transformation (if applicable, $\approx$ 6–9%).

The photometry described in the earlier paragraph inevitably contains a seeing-dependent fraction of the host light directly at the position of the transient. This contribution is best removed via differential imaging with deep reference frames from the same instrument/filter combination taken after the transient has faded completely. Given the vast number of different observers taking part in our photometry campaign, however, this procedure was not feasible in our case for all images. We instead used reference frames from a single telescope (Gemini-N, obtained $\sim$ 270 days after the explosion) in three filters. We measure: $g' = 24.62 \pm 0.10$, $r' = 24.09 \pm 0.09$, and $i' = 24.09 \pm 0.09$ mag, i.e. a host light contribution of 10%, 7% and 7% in $g'r'i'$ at maximum SN light. To estimate the fraction in different filters, we scaled the above numbers to the respective filters using the SED of the host. We assume that this factor is similar for all data from various telescopes. We note that the values in Table A.1 are *not* corrected for this host contribution.

3. The transient accompanying GRB 120422A

Figure 2 displays the brightness evolution of the transient accompanying GRB 120422A from X-rays to the NIR. During the first three days, its brightness in the UVOT filters gradually decreases with a decay slope of $\alpha = 0.2$ that is followed by a rebrightening peaking at $\sim$ 20 days post-burst. The time scale and the colour evolution of the rebrightening are comparable to those of GRB-SNe (e.g. Zeh et al. 2004). The initially decaying transient could therefore be a superposition of the afterglow and the thermal emission of the cooling photosphere after the SN emerged. Key to understanding the evolution of the transient accompanying GRB 120422A is disentangling the different radiation components. In the following sections we will present our results on each component.

3.1. The stellar envelope cooling-phase

Figure 3 displays spectral energy distributions at 0.054 and 0.267 days after the GRB. While afterglows have spectra formed by piecewise-connected power laws from radio to X-rays (Sari et al. 1998), the cooling phase of the stellar envelope that was heated by the SN shock break-out is characterised by thermal emission peaking in the UV.

The early UV emission is indeed well fitted with a blackbody (for details see Sect. 3.2.3). We measure a blackbody temperature of $kT_{\rm obs} = 14$ eV and a blackbody radius of 9×10^{13} cm at $T_0 + 0.054$ days. These values are consistent with expectation from the shock-break-out model (e.g. Ensman & Burrows 1992; Campana et al. 2006, and references therein) and lie in the ballpark of observed values of Ib/c SNe, such as 1993J (Richmond et al. 1994, 1996; Blinnikov et al. 1998), 1999ex (Stritzinger et al. 2002), 2008D (Soderberg et al. 2008; Malesani et al. 2009; Modjaz et al. 2009) and 2011dh (Arcavi et al. 2011; Soderberg et al. 2012; Ergon et al. 2013), and of the GRB-SNe 2006aj (Campana et al. 2006) and 2010bh (Cano et al. 2011a; Olivares E. et al. 2012).

The observed decline in the u band between its first detection and $T_0 + 2.8$ days and the local minimum in the light curve before the SN rise is $\sim$ 2 mag. It is comparable to that observed in GRB 060218 (Campana et al. 2006). However, for this event, these authors also reported a rise in brightness up to 0.57 days after the burst (shifted to the observer frame of GRB 120422A). This initial rise is not present in our data, although the first observation was at 86.4 s after the onset of the γ-ray emission.

3.2. The afterglow emission

3.2.1. X-rays

Zhang et al. (2012) reported that the early X-ray emission ($t < 200$ s) is consistent with high-latitude emission from the prompt emission phase (e.g. Fenimore & Sumner 1997;

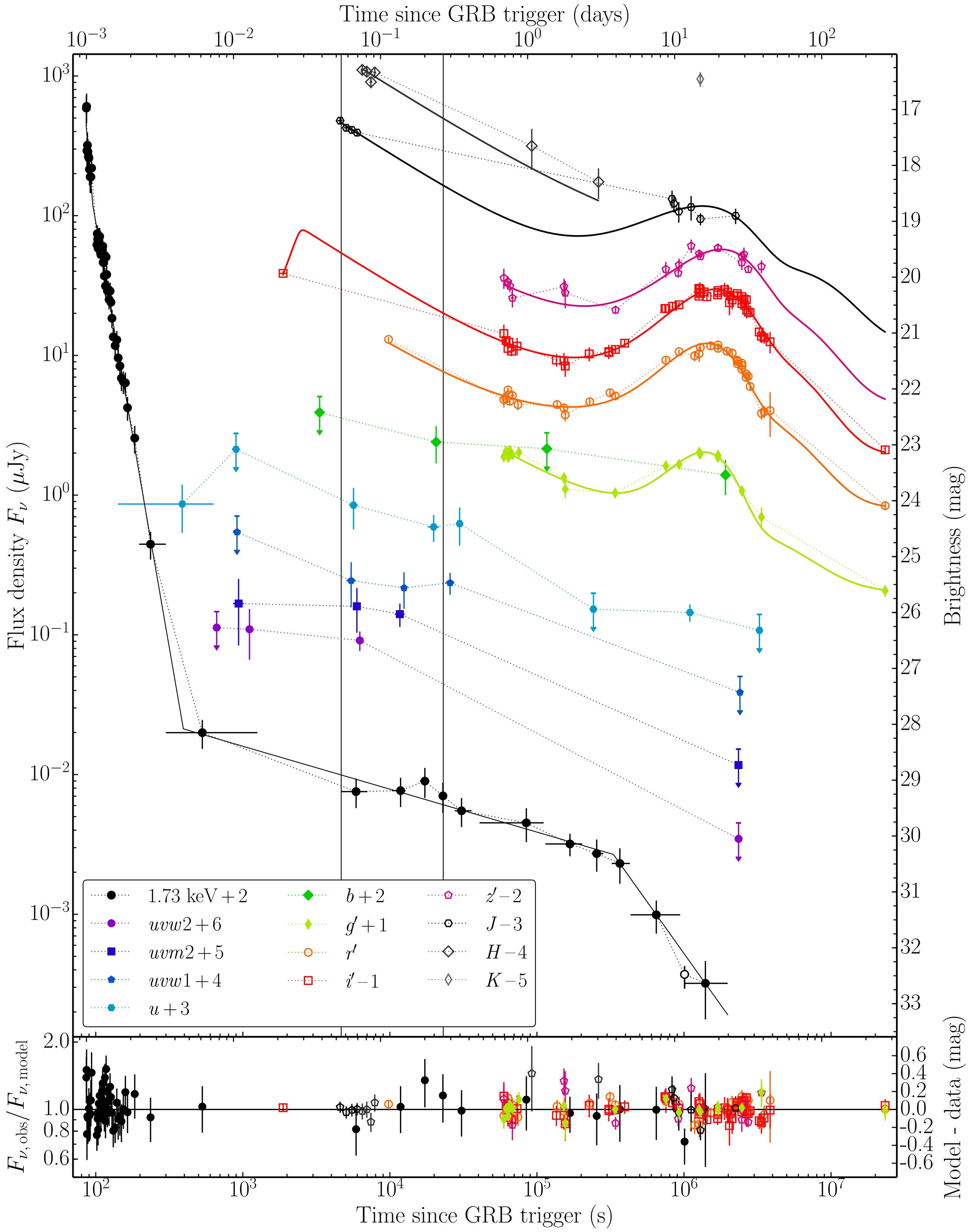

Fig. 2. X-ray, optical and NIR light curves of the transient following GRB 120422A. Arrows indicate 3σ upper limits. The UVOT v-band upper limits are very shallow and not displayed. Data in the $g'r'i'z'J$-bands were modelled with a SN 1998bw template at $z = 0.283$ superposed on a power law (where the slope was identical in all bands) using the formalism in Zeh et al. (2004). The best-fit model parameters are shown in Table 3. Model light curves in bluer or redder filters are not shown since they would require extrapolation of the spectral range of the SN1998bw template. Fit residuals are displayed in the bottom panel. The *XMM-Newton* observation was carried out at 980 ks (open dot). The shifts (in magnitude) of the different bands are given in the legend. To convert the X-ray light curve to flux density, we assumed a spectral slope of $\beta = 0.9$ and no spectral evolution (for details on the SED modelling see Sect. 3.2.3). Both assumptions have no implications on our analysis. The *XMM-Newton* data point was discarded from the light curve fit because of uncertainties in the cross-calibration between *Swift*/XRT and *XMM-Newton*. The vertical lines indicate the epochs of the X-ray-to-NIR SEDs presented in Sect. 3.2.3.

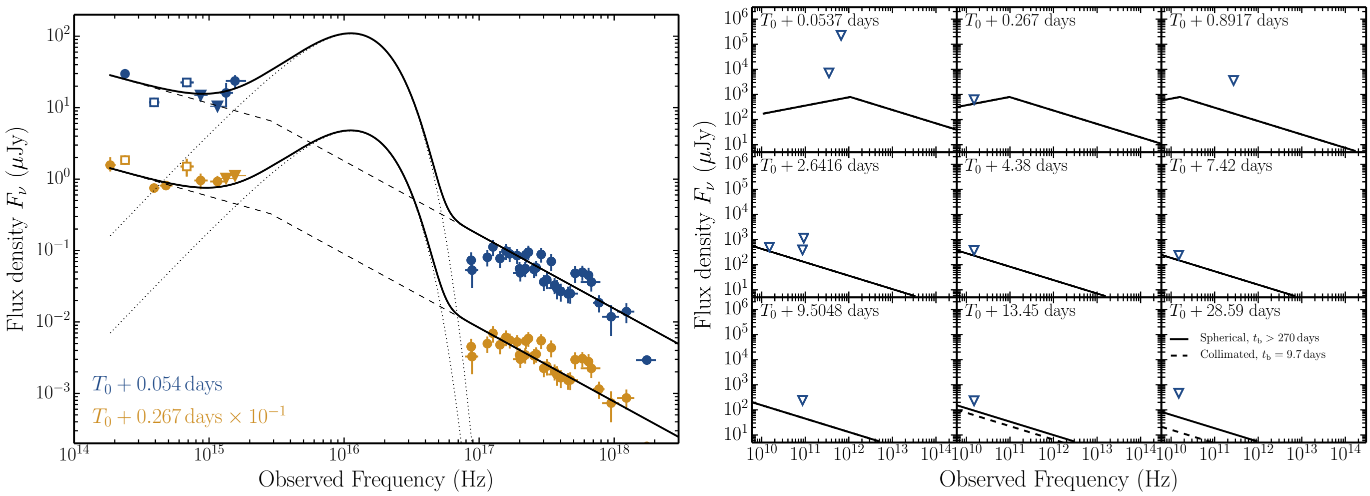

Fig. 3. ***Left***: Spectral energy distribution from the NIR to the X-ray at early epochs. The optical-to-X-ray SEDs are best described by absorbed broken power law (dashed lines) models modified by a blackbody (dotted lines). Data excluded from fits are shown as empty symbols and upper limits by triangles. ***Right***: Radio-to-sub-mm SEDs at the epochs listed in Table 2. The NIR-to-X-ray SED from $T_0 + 0.267$ days was extrapolated to radio frequencies and evolved in time for a collimated and spherical expansion of the blast-wave (for details see text). The AMI-LT measurement from $T_0 + 2.38$ was shifted to 2.6416 days, assuming the injection frequency to be blueward of the observed bandpass and using the scaling relations in Sari et al. (1998). This has no implications on our analysis.

Kumar & Panaitescu 2000; Dermer 2004), with evidence for small-scale deviation from power-law models (Starling et al. 2012), possibly due to a thermal component as seen in other GRBs (e.g. Campana et al. 2006; Page et al. 2011; Starling et al. 2011, 2012; Sparre & Starling 2012; Friis & Watson 2013). Friis & Watson (2013) suggested that such a thermal component is not produced by the stellar photosphere but by the photosphere of the GRB jet. In the following, we will focus on the emission at > 200 s after the burst.

At the time of our *XMM-Newton* observation the X-ray spectrum is adequately fit as an absorbed power-law with a spectral slope of $\beta = 94^{+0.12}_{-0.11}$, with absorption entirely consistent with the Galactic column (3.71×10^{20} cm^{-2}). The spectral slope is consistent with that derived from the late time XRT spectrum ($\beta = 0.98 \pm 0.13$), and suggests no late time spectral changes ($t > 4600$ s). The spectral slope is typical for GRB afterglows at that phase.

The joint XRT and *XMM-Newton* light curve is shown in Fig. 2, where we converted the XRT observations to flux based on the mean spectral index of the system (following Evans et al. 2009), and then added the *XMM-Newton* observations assuming their measured spectral parameters. The X-ray light curve is adequately fit by a multiply broken power-law with indices of $\alpha_1 = 12.7 \pm 4.1$, $\alpha_2 = 6.09 \pm 0.16$, $\alpha_3 = 0.31 \pm 0.04$, $\alpha_4 = 1.48 \pm 0.40$, and break times of $t_{b,1} = 95.3 \pm 3.2$ s, $t_{b,2} = 394 \pm 19$ s and $t_{b,3} = 330.5 \pm 89.0$ ks, the resulting χ^2/d.o.f. $= 43.5/54$. We note that an early break is needed to fit the WT settling mode exposures, which has a chance improvement probability of $\sim 6.6 \times 10^{-5}$.

The steep-to-shallow-to-normal decay-phase evolution is typical for X-ray afterglows of high-L GRBs (Nousek et al. 2006; Evans et al. 2010). In particular, the very rapid decay phase ($\propto t^{-13}$) unambiguously points to high-latitude emission, and has not been observed for low-L GRBs so far.

3.2.2. Optical/NIR

As mentioned before, the thermal emission of the cooling photosphere has an intrinsically blue spectrum and does not significantly contribute to the integrated emission in the optical and NIR. Therefore, the optical/NIR emission can be decomposed into three distinct emission components: *i*) the afterglow, which can be modelled with simple and broken power-law models; *ii*) the supernova; and *iii*) the host galaxy, which can be accounted for by a constant flux. To characterise the SN component, we follow the approach in Zeh et al. (2004). They used the multi-color light curves of the prototypical GRB-SN 1998bw (Galama et al. 1998; Patat et al. 2001) as templates. They derived the SN 1998bw light curves at the given GRB redshift, and in the given observed band (including the cosmological k-correction), and additionally modified the template with two parameters. The luminosity factor k determines the SN peak luminosity in a given band in units of the SN 1998bw peak luminosity in that band. The stretch factor s determines if the light curve evolution is faster ($s < 1$) or slower ($s > 1$) than that of SN 1998bw, whereby the actual evolutionary shape remains the same, and the explosion time is always identical to the GRB trigger time. However, we limit the SN modelling to the $g'r'i'z'J$ bands. Model light curves in bluer or redder filters require extrapolating the spectral range of the SN1998bw template.

The results of our fits are given in Table 3. In this section we report on the afterglow properties and on those of the SN in Sect. 3.3.2. The light curve fits reveal that there is indeed a power-law component, and hence provide strong evidence for an optical/NIR afterglow accompanying GRB 120422A. The fit with a simple power law makes the assumption that the afterglow light curve does not steepen until $T_0 + 270.2$ days. For a collimated outflow the observer sees the edge of the jet at a certain time, resulting in a significant steepening (Sari et al. 1999). A jet break after 270 days has been observed in GRB 060729 (Grupe et al. 2010, see also Perley et al. 2013a for a further example of a very late jet break), but a typical value is ~ 0.6 day (rest-frame; e.g. Zeh et al. 2006; Racusin et al. 2009). We refitted the light curve with a smoothly broken power law (Beuermann et al. 1999), where the post-break decay slope was fixed to 2. The pre-break slope is identical to the value from the simple power law fit. The jet-break time of 9.7 ± 4.4 days (observer frame) is still large and very uncertain, but its value is more consistent with the observed distribution in Racusin et al. (2009). A reason for this large uncertainty in the break time is the brightness of the SN.

Both afterglow models over-predict the i'-band brightness at T_0+1880 s by 0.9 mag. The required rise could be either due to the crossing of the injection frequency ν_m or due to the coasting phase before the afterglow blast-wave begun decelerating. In the former case the rise slope α_r is -0.5 (with $F_\nu \propto t^{-\alpha_\mathrm{r}}$; Sari et al. 1998), and in the latter between -3 and -2 for constant-density medium and > 0.5 for a free-stellar-wind density profile (Shen & Matzner 2012).

The crossing of the injection frequency ν_m is by definition a chromatic feature. It evolves $\propto t^{-3/2}$ (Sari et al. 1998). This means the ratio between break times in two different bands has to obey $t_2/t_1 = (\nu_2/\nu_1)^{-2/3}$. The J band has the earliest detection after the first i' observation and is not affected by the thermal emission from the cooling stellar photosphere. Since the J-band light curve is only decaying, ν_m crossed this band at $t < 4550$ s after the burst and hence the i' band at $\lesssim 3260$ s. Already in the limiting case, the expected i' band magnitude is 0.24 mag brighter than the observed value. Given the small photometric error of 0.04 mag makes the deviation statistically significant and hence this scenario unlikely. The blast-wave's coasting into a free-stellar-wind ambient density profile is also in conflict with our data, since we detect a clear rise and not a shallow decay.

A steep rise of $\alpha_\mathrm{r} = -2$ to -3 is fully consistent with our data. In both cases, the break time is ~ 2550 s (observer frame). We hence identify the coasting phase into a constant-density circumburst medium as the most likely scenario. Since the break time determines the transition from the coasting to the deceleration phase, it can be used to measure the initial Lorentz factor Γ_0 of the decelerating blast-wave (Sari & Piran 1999; Panaitescu & Kumar 2000; Mészáros 2006). Following Molinari et al. (2007), we measure $\Gamma_0 \sim 60$ using the observed break time and the measurement of the energy $E_\mathrm{iso} = 4.5 \times 10^{49}$ erg released during the prompt γ-ray emission.

3.2.3. The SED from the radio to the X-rays

To characterise the afterglow properties in more detail, we model the joint NIR-to-X-ray spectral energy distribution (SED). We limit this analysis to $< T_0 + 1$ day, since SN 2012bz started contributing a non-negligible amount of flux to the integrated light at later times. We choose the epochs $T_0 + 0.054$ days and $T_0 + 0.267$ days to match the dates of the sub-mm/mm observations. The optical and NIR fluxes were obtained through interpolation between adjacent data points.[12] Errors were estimated by interpolation. The flux scales of the XRT and XMM (MOS1, MOS2, PN) data were adjusted to the brightness of the X-ray afterglow at the respective epochs.

The NIR-to-X-ray SEDs, shown in Fig. 3, have in common that the UV emission is dominated by radiation from the cooling stellar envelope after the shock break-out (Sect. 3.1). To account for this thermal emission, we fit the NIR-to-X-ray SED with absorbed simple and broken power-law models modified by a blackbody model using `Xspec` v12.8.0. The blackbody model is defined by:

$$BB\,(E;\,C,\,T) = 1.0344 \times 10^{-3}\, C\, \frac{E^2\,\Delta E}{\exp\left(E/k_\mathrm{B}\,T\right) - 1}$$

where the numerical constant C is defined as $R^2_\mathrm{km}/D^2_{10\,\mathrm{kpc}}$, where R is the blackbody radius in km, D the distance in units of 10 kpc, k_B the Boltzmann constant, T the temperature in units of keV, E the energy and ΔE is the width of the energy bin.

Both SEDs are best fitted by a broken power law with $\beta_\mathrm{o} \sim 0.5$ and $\beta_\mathrm{x} \sim 1$ and a break energy of ~ 4 eV. The difference in the slopes is consistent with the expected value for synchrotron radiation, if the cooling break is between both bands (Sari et al. 1998). This is a further circumstantial evidence that the optical and X-ray emission are produced by the afterglow. Given the sparse sampling of the optical/NIR bands, we fit both epochs simultaneously and fix the difference in the spectral slopes to 0.5 and set the break energies to identical values. The joint fit gives a spectral slope of $\beta_\mathrm{o} \sim 0.46$ in the optical (i.e. $\beta_\mathrm{x} = 0.96$), a break energy of ~ 4 eV, no evidence for a significant host absorption at X-ray energies, and a blackbody temperature of ~ 16 eV and radius of $\sim 7 \times 10^{13}$ cm at 1.4 hours after the burst. The blackbody component in the second epoch is barely constrained because of the limited amount of UV data. The combined fit statistics is 114.7/74 d.o.f.

The peak of an afterglow spectrum is typically at cm/sub-mm wavelengths, and usually crosses this band within the first week. We therefore extrapolate the afterglow SED from T_0+0.267 days to radio wavelengths (Fig. 3) and evolve the SED to all epochs of the radio and sub-mm observation listed in Table 2, using the scaling relations for the injection frequency and the peak flux density for a spherical expansion and a post-jet beak evolution from Sari et al. (1998, 1999). In both dynamical scenarios, the peak flux density is $\lesssim 800\ \mu$Jy, corresponding to a specific luminosity of $\lesssim 2 \times 10^{30}\ \mathrm{erg\,s^{-1}\,Hz^{-1}}$ before the jet break occurred.

3.3. *Supernova properties*

3.3.1. Supernova spectrum

Our spectra of SN 2012bz are displayed in Fig. 4. The very early spectra are dominated by a smooth power-law continuum, characteristic of GRB afterglows. At around 4.7 days, after the transient started re-brightening (Fig. 2), the shape of the spectrum changes and it becomes redder. By May 1 (8.8 days after the GRB), the spectrum has clearly started to resemble that of a supernova with broad lines (Sect. 5.1.1; Malesani et al. 2012a; Sánchez-Ramírez et al. 2012; Wiersema et al. 2012). By May 10 (18.7 days

[12] In the UV, there are cases where one of the adjacent data points is an upper limit but the epoch of the SED is very close to the time of the detection ($\Delta t < 0.1$ dex). In these cases we treated the interpolated data point as detection but not as upper limit.

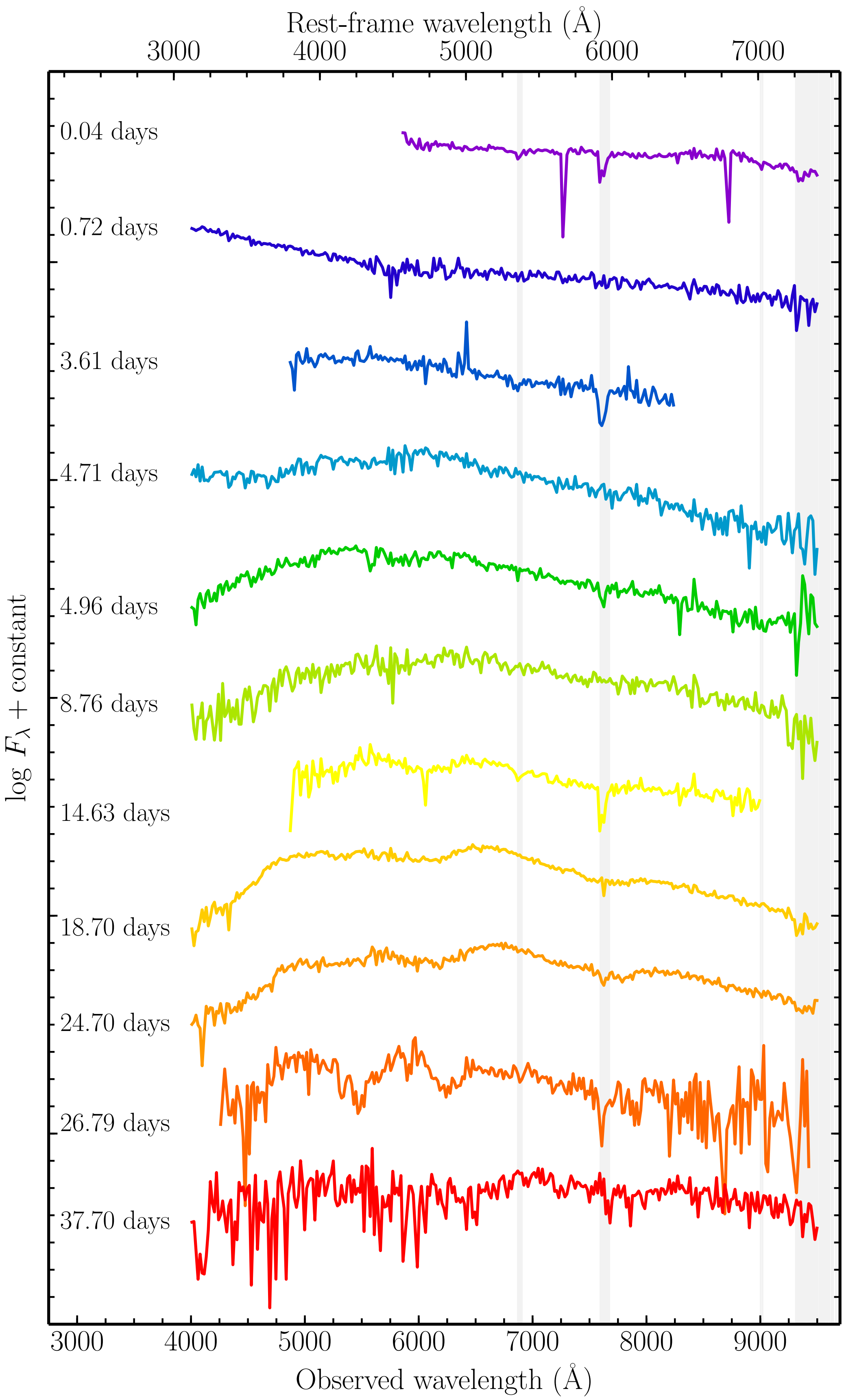

Fig. 4. Spectral evolution of the optical transient accompanying GRB 120422A. The first two epochs show a smooth power-law-shaped continuum, characteristic of GRB afterglows. After the transient started re-brightening, the shape of the spectrum becomes redder. At 8.8 days after the GRB, the spectrum has clearly started to resemble that of a broad-lined SN. At 18.7 days, the transformation is complete and the spectra look similar to other GRB-SNe. All spectra were shifted vertically by an arbitrary constant. They were rebinned (18 Å) to increase S/N for presentation purposes. We only display spectra with a large spectral range. Strong telluric lines (transparency $< 20\%$) are highlighted by the grey-shaded areas.

Table 3. Properties of the SN modelling

Band	Host magnitude (mag)	Luminosity factor k	Stretch factor s	χ^2/d.o.f.
Simple power law + free host magnitude $\alpha_1 = 0.69 \pm 0.02$				
g'	24.65 ± 0.12	0.86 ± 0.03	0.94 ± 0.02	
r'	24.06 ± 0.04	1.25 ± 0.02	0.89 ± 0.02	
i'	24.17 ± 0.08	1.10 ± 0.01	0.92 ± 0.01	194.9/146
z'	24.31 ± 0.12	0.99 ± 0.02	0.92 ± 0.03	
J	24.22 ± 0.22	1.12 ± 0.09	0.74 ± 0.12	
H	...	...	...	
Smoothly broken power law + fixed host magnitude $\alpha_1 = 0.67 \pm 0.02$, $\alpha_2 = 2.00$ (fixed), t_b (days) $= 9.7 \pm 4.4$, $n = 10$ (fixed)				
g'	24.62	0.88 ± 0.05	0.97 ± 0.02	
r'	24.09	1.25 ± 0.02	0.90 ± 0.01	
i'	24.09	1.11 ± 0.02	0.92 ± 0.01	186.6/150
z'	24.15	0.99 ± 0.03	0.92 ± 0.03	
J	23.96	1.06 ± 0.09	0.68 ± 0.09	
H	23.84	...	...	

Notes. Best-fit parameters of the $g'r'i'z'JH$ band light curve fits. We modelled $g'r'i'z'J$ light curves with a SN1998bw template redshifted to $z = 0.2825$, as described in Zeh et al. (2004), superposed on a simple power law or smoothly broken power law (Beuermann et al. 1999), where α denote the decay slopes, t_b the break time and n the smoothness, to account for the early emission and the flux from the host galaxy at the explosion site. Note, for the H band we used the afterglow models. We assumed that the afterglow component evolves achromatically from the g' to the H band. The supernova and afterglow light curve is equally well fitted with the two models. See Sect. 3.3.2 for details.

after the GRB), the transformation is complete and our X-shooter spectra from +18.7 and +24.7 days are very similar to those of other broad-lined Type Ic SNe accompanying GRBs (Fig. 11). The Magellan spectrum obtained 26.8 days after the GRB has a low S/N despite showing absorption troughs at locations consistent with the previous data and should be interpreted with great caution. The modelling of the spectral evolution will be presented in a forthcoming paper.

Usually, GRB-SN expansion velocities are reported using Si IIλ6355, with the Ca II NIR triplet at 8600 Å reported sometimes as the only alternative (Patat et al. 2001; Hjorth et al. 2003; Chornock et al. 2010; Bufano et al. 2012). In the case of SN 2012bz, the Si II line is contaminated by the telluric A-band, while the Ca IR triplet is redshifted outside the optical spectrum. For this reason, we chose to measure the expansion velocities based on the Fe IIλ5169 feature. In addition, this feature appears earlier than the Si II feature and its minimum is easier to locate as it lies between two clearly visible maxima (Fig. 4, 11). This makes it a potentially better expansion velocity tracer for GRB-SNe than Si II, which is super-imposed on a blue continuum and it is not always easy to locate and measure, especially at early times.

We have used the fiducial rest-wavelength of 5169 Å for Fe II, as done e.g. in Hamuy & Pinto (2002) for the expansion velocities of Type IIP SNe. We stress that even if this identification is not correct for GRB-SNe, due to blending, these measurements are still valuable in order to monitor the expansion velocity evolution and for comparison between different objects as long as the measurements are done consistently. Based on these assumptions, we present the first, to our knowledge, diagram of GRB-SNe expansion velocities, based on Fe IIλ5169 (Fig. 5). The velocities (of the order of 5000–50000 km s^{-1}) are in the range measured for other SNe associated with GRBs. SN 2010bh shows the fastest explosion velocities as seen from Si II, while SN 2006aj the slowest (Chornock et al. 2010; Bufano et al. 2012). SN 2012bz shows large velocities at 3 days past explosion (the earliest spectrum where a measurement is possible) and slowing down to 17000 km s^{-1} $\sim$ 20 days later. This behaviour is very similar to SN 2003dh associated with the high-L GRB 030329 (Hjorth et al. 2003).

3.3.2. Absolute magnitude

The luminosities of SNe are usually reported in the rest-frame V band. The r' bandpass (observer frame) partly overlaps with the rest-frame V band, though it is not identical. We compute the k-corrected V-band magnitude from the r'-band maximum, following Hogg et al. (2002) and using the X-shooter spectrum from T_0 + 18.7 days (i.e. $<$ 2 days after the maximum in r'-band) as a weighing function. The peak luminosity of $M_\mathrm{V} = -19.7$ mag is 0.3 mag brighter than SN 1998bw, using the face value of $M_\mathrm{V} = -19.4$ mag from Cano et al. (2011b).

Measuring the SN luminosity by using a k-correction from the observed spectrum is the most direct and accurate approach. However, the number of spectroscopically confirmed GRB-SNe is still small. Moreover, optical spectroscopy is limited to mostly low redshifts ($z < 0.3$), because of the prohibitively long exposures required for a $M_\mathrm{V} \sim -19$ mag SN at higher redshifts. In addition, the useful wavelength range is reduced to the red part of the observed spectrum due to line blanketing by iron, as rest-frame UV moves into the optical V band, (Filippenko 1997). An alternative approach is to look for "late red bumps" in afterglows light curves, which are due to the GRB-SNe. The best fit parameters of the SN bump with SN 1998bw templates in the $g'r'i'z'J$ bands, as detailed in Sect. 3.2.2, are displayed in Table 3. The fit reveals that SN 2012bz is 0.3 mag more luminous than SN 1998bw in the observed r' band and the evolution is slightly faster than that of SN 1998bw, and it is somewhat redder.

3.3.3. The explosion-physics parameters

The peak and width of a SN light curve are determined by the explosion-physics parameters, such as ejecta mass M_ej, ^{56}Ni mass M_Ni, and kinetic energy E_k of the SN ejecta. These values are estimated from the bolometric light curve. An estimate of the bolometric light curve was constructed using $g'r'i'z'$ photometric points, as coverage outside these bands is limited around the SN peak. The light curves in each filter were fitted with spline interpolations starting at 2 days past the GRB trigger, such that an estimated magnitude for all four bands was available at each epoch of observation. Magnitudes were converted into monochromatic fluxes at the effective (rest-frame) wavelengths of the filters for every epoch to produce an SED.[13] Each SED was then integrated over the limits of the filter wavelength range,

[13] Since we are evaluating the SED for every observation, nearby epochs (within $<$ 0.2 day of each other) were first calcu-

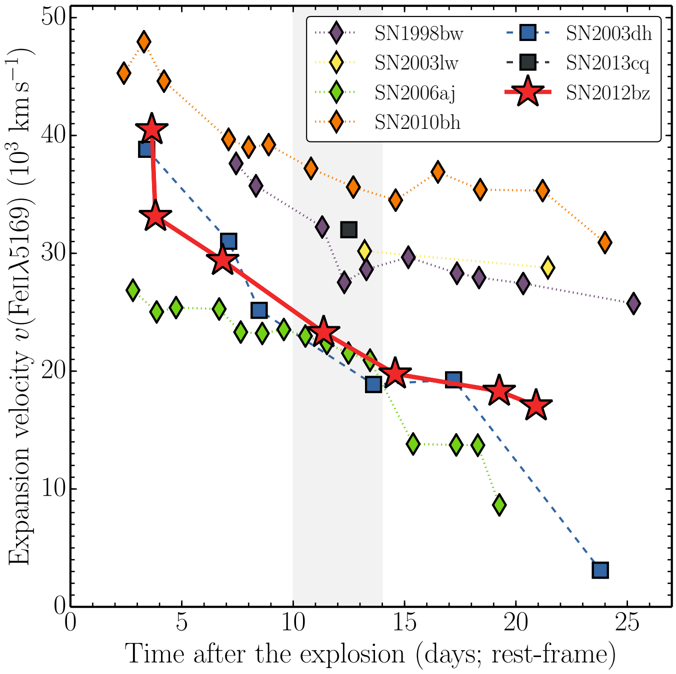

Fig. 5. Evolution of the expansion velocities measured from Fe II λ5169 for SN 2012bz and six GRB-SNe of low (diamonds) and high-luminosity GRBs (boxes) with good spectroscopic data. Measurements were performed on our data as well on the spectra of Patat et al. (2001), Hjorth et al. (2003), Malesani et al. (2004), Pian et al. (2006), and Bufano et al. (2012). The value of SN 2013cq was taken from Xu et al. (2013). The grey shaded area displays the interval of observed GRB-SN peak times.

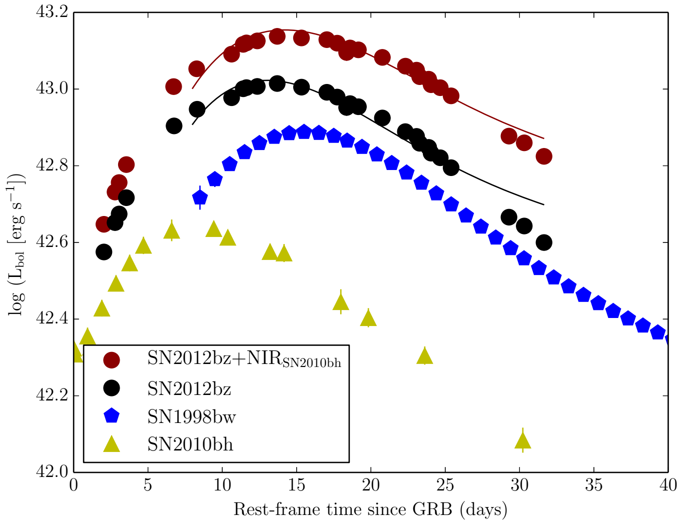

Fig. 6. Pseudo-bolometric light curves of SN 2012bz from direct integration of the SED over $g'r'i'z'$ filters, and including a NIR contribution as found for SN 2010bh. For comparison the $UBVRI$ light curve of SN 1998bw (Clocchiatti et al. 2011) and the $g'r'i'z'JH$ light curve of SN 2010bh are shown (Olivares E. et al. 2012). The models for SN 2012bz are shown as solid lines. Early light-curve time data are not fitted as the analytical model does not account for other non-negligible sources of luminosity at these times (Sect. 3.3.3). Only photometric and calibration uncertainties are included in the error bars which are usually smaller than the size of the plot symbol.

i.e. the blue edge of g' and the red edge of z' ($\sim$ 3000–8000 Å). The SED was tied to zero flux at these limits, which were defined as the wavelength at which the respective filter's normalised transmission curve falls below 10%. The integrated fluxes were converted to luminosities using the redshift and cosmology adopted previously. The resulting light curve (Fig. 6) gives a luminosity of the SN over approximately the optical wavelength range.

Contributions to the flux outside this regime, however, are not insignificant, with the optical accounting for $\sim 50-60\%$ of the bolometric flux for stripped-envelope SNe (Lyman et al. 2013). Of particular importance is the contribution from the NIR, wherein the fraction of the total luminosity emitted increases with time, reaching a comparable contribution to the optical within 30 days (e.g. Valenti et al. 2008; Cano et al. 2011a). We estimate this missing NIR flux by using the fractional NIR flux of a similar event, as done in Cano et al. (2011a). A photometric study by Olivares E. et al. (2012) of the low redshift ($z = 0.059$) XRF 100316D/SN 2010bh contains well sampled light curves in the $z'JH$ bands, extending upon our rest-frame wavelength limits. The contribution of wavelengths $>$ 8000 Å to the flux was determined by first integrating SN 2010bh's dereddened SED over the same wavelength range used for SN 2012bz above, and then over the wavelength range redward of 8000 Å. Thus, for each epoch of observation, we obtain the NIR contribution as a fraction of the optical flux. The phase of the contributions were normalised so $t = 0$ was the peak of the respective SNe, and stretched by a factor $\Delta m_{15,\ (3000-8000)\,Å}$ to match the light curve shape of the two SNe ($\Delta m_{15,\ (3000-8000)\,Å} = 0.78$ for SN 2012bz, 1.00 for SN 2010bh).[14] The fractional values were interpolated using a smooth spline, in order to sample it at the epochs of observations of SN 2012bz, and the appropriate amount was added to the optical flux. This gives a NIR corrected light curve covering 3000–17000 Å. No attempt was made to account for flux missed below 3000 Å due to the paucity of data constraining the UV in such objects. However, contributions from the UV account for only $\sim 5-15\%$ of the bolometric flux around peak (Lyman et al. 2013).

The bolometric light curve was modelled using the simplified analytical prescription of Arnett (1982), updated by Valenti et al. (2008), to obtain estimates of the M_{Ni} M_{ej} and E_{K}. Since obtaining a truly bolometric light curve is unfeasible, we use our optical and optical+NIR correction light curves as approximations. Our data cover the photospheric phase of SN evolution, when the ejecta are considered optically thick. The opacity is chosen to be $\kappa = 0.07$ cm^2 g^{-1} (see Cano et al. 2011a). To constrain the $E_{\mathrm{K}}/M_{\mathrm{ej}}$ ratio, a *scale velocity* is required (see equation 54 in Arnett 1982), this is taken to be the photospheric velocity (v_{ph}) at peak. Fe II lines are a good tracer of v_{ph} (Valenti et al. 2011), and the peak of the pseudo-bolometric light curve occurs at ∼13.9 days (from fitting low-order polynomials around peak). Using data in Fig. 5 we take 20500 km s^{-1} as an

lated individually and then averaged when producing the final light curve for clarity.

[14] Phillips (1993) introduced Δm_{15} as the decline in the brightness between the maximum and 15 days post maximum in B band.

estimate of $v_{\rm ph}$ at peak by linearly interpolating between the measurements taken from spectra at epochs 11.380 days and 14.575 days.

Fitting to the optical bolometric light curve reveals the following parameters: $M_{\rm Ni} = 0.40 \pm 0.01$ M$_\odot$, $M_{\rm ej} = 4.72 \pm 0.04$ M$_\odot$ and $E_{\rm K} = 3.29 \pm 0.03 \times 10^{52}$ erg, and when including the NIR contribution from SN 2010bh, we obtain $M_{\rm Ni} = 0.58 \pm 0.01$ M$_\odot$, $M_{\rm ej} = 5.87 \pm 0.03$ M$_\odot$ and $E_{\rm K} = 4.10 \pm 0.03 \times 10^{52}$ erg. The first 8 days were ignored in the fit as contributions from other sources (GRB afterglow and cooling phase following the shock break-out) would compromise the assumptions of the SN model.

It is crucial to note that the errors quoted here include only the statistical uncertainties relating to the construction of the pseudo-bolometric light curves. Systematic errors arise from both the simplifying assumptions in the model (spherical symmetry, centrally concentrated ^{56}Ni mass etc.) and our choice of parameters for the fit, which typically dominate the statistical errors. For example taking an uncertainty in $v_{\rm ph}$ of 2000 km s^{-1} translates into an error in $M_{\rm ej}$ and $E_{\rm K}$ of $\sim 10\%$ and $\sim 25\%$, respectively. The two-component model for very energetic supernovae ($E_{\rm k} \gtrsim 5 \times 10^{51}$ erg) by Maeda et al. (2003) would also suggest we are only observing the outer, lower density region of the ejecta during the photospheric phase ($\lesssim 30$ days), and a fraction is hidden in a denser, inner component during this time. Although the afterglow component is not expected to contribute significantly around the SN peak, given that different afterglow models do not significantly affect the k, s parameters (Sect 3.3.2), potential contamination by underlying host galaxy light is included in this bolometric light curve (Sect. 2.3).

Melandri et al. (2012) modelled SN 2012bz using a scaled spectral model for SN 2003dh to obtain estimates of the physical parameters. They obtained values of $M_{\rm Ni} \approx 0.35$ M$_\odot$, $M_{\rm ej} \approx 7$ M$_\odot$ and $E_{\rm K} \approx 3.5 \times 10^{52}$ erg using a bolometric light curve covering 3300–7400 Å. Comparing these to our values for the optical (3000–8000 Å) bolometric light curve, the $M_{\rm Ni}$ values are in good agreement, given our slightly extended wavelength range, $E_{\rm K}$ values are consistent, however their derived ejected mass is larger than our measurement. Differences could be caused by the choice of photospheric velocity $v_{\rm ph}$, asymmetries, or varying opacity κ, which spectral modelling can account for.

4. Environments

Absorption and emission lines are powerful diagnostics to characterise the gas and dust phase of interstellar media, such as the extinction, metallicity and star-formation rate (SFR). Since long GRBs are associated with massive stars, these diagnostics give the unique opportunity to study star-forming regions in distant galaxies. In the following, we present our findings on the explosion site, on the host galaxy and its large scale environment (for an independent analysis see Levesque et al. 2012).

4.1. The explosion site

The X-shooter spectrum, obtained on 23 April (17.2 hours post burst; see Fig. C.1), exhibits two absorption lines, which we identify as Mg II $\lambda\lambda$2796,2803 (see Table 4). After applying the heliocentric correction, we measure a mean absorption-line redshift of $z_{\rm abs} = 0.28253 \pm 0.00008$ (the error denotes the standard error of the mean), refining the redshift measurements of Schulze et al. (2012b) and Tanvir et al. (2012).

Table 4. Absorption and emission lines at the explosion and the host site

$\lambda_{\rm obs}$(Å)	Transition	redshift	$EW_{\rm obs}$(Å)	$F \times 10^{16}$ (erg cm^{-2}s^{-1})
Explosion site ($\langle z \rangle_{\rm abs} = 0.28253$, $\langle z \rangle_{\rm em} = 0.28259$)				
3586.22	Mg II λ2796	0.2824	3.25 ± 0.42	...
3595.95	Mg II λ2803	0.2827	1.86 ± 0.46	...
...	Mg I λ2852	...	< 1.57	...
4779.79	[O II] λ3727	0.28245	...	0.09 ± 0.01
4783.37	[O II] λ3729	0.28245	...	0.16 ± 0.01
5046.00	Ca II λ3934	0.2825	...	0.75 ± 0.25
...	Ca II λ3968	...	< 1.08	...
6236.87	Hβ	...	...	0.05 ± 0.04
6362.18	[O III] λ4959	0.28262	...	0.05 ± 0.02
6423.34	[O III] λ5007	0.28255	...	0.19 ± 0.02
8419.55	Hα	0.28257	...	0.24 ± 0.01
8447.92	[N II] λ6583	0.28286	...	0.06 ± 0.02
8616.96	[S II] λ6717	0.28261	...	0.03 ± 0.01
Host site (PA = 41°; $\langle z \rangle_{\rm em} = 0.28256$)				
4780.16	[O II] λ3727	0.28254	...	2.30 ± 0.03
4783.73	[O II] λ3729	0.28254	...	3.50 ± 0.67
4920.46	Hη	0.28255	...	0.09 ± 0.01
4963.37	[Ne III] λ3869	0.28262	...	0.27 ± 0.02
4979.74	Hζ	0.28248	...	0.20 ± 0.01
5093.04	Hϵ	0.28250	...	0.19 ± 0.02
5262.10	Hδ	0.28252	...	0.30 ± 0.02
5567.86	Hγ^a	0.28242	...	0.59 ± 0.04
6236.89	Hβ	0.28260	...	1.28 ± 0.04
6362.15	[O III] λ4959	0.28261	...	0.83 ± 0.03
6423.60	[O III] λ5007	0.28261	...	2.51 ± 0.05
8419.75	Hα^b	0.28260	...	5.36 ± 0.05
8446.38	[N II] λ6583	0.28262	...	0.81 ± 0.04
8616.90	[S II] λ6717	0.28260	...	0.91 ± 0.02
8635.40	[S II] λ6731	0.28260	...	0.67 ± 0.03

Notes. The reported wavelengths were derived from the first momentum of a line profile (see Fig. C.1 and C.2). The fluxes were corrected for foreground extinction. [(a)] Blended line. [(b)] This value is the total flux of both velocity components.

Both lines lie in a rather noisy part of the spectrum. To measure their equivalent widths, we rebinned the spectrum by a factor of two to increase the S/N (i.e. a wavelength binning of 0.4 Å), and fixed the aperture size for the weaker Mg II line to 100 km s^{-1} (the FWHM of the Mg IIλ2796 absorption line). Their rest-frame EWs are listed in Table 4. The observed line ratio of 1.7 ± 0.5 is not well constrained. It is consistent with the theoretical expected line ratio for an optically thin line but also for a saturated line. Assuming the weak line regime, we can place a lower limit of $\log N \geq 13.8$ on the Mg II column density. When Mg II is detected, three further absorption lines are usually detected at longer wavelengths, as well: Mg Iλ2852 and Ca II$\lambda\lambda$3934,3969. Only Ca IIλ3934 is detected at $\lesssim 3\sigma$ c.l. To place limits on their rest-frame EWs, we measure the noise within an aperture of $2 \times$ FWHM (Mg IIλ2796) at the wavelength of each line. Table 4 displays their derived upper limits. We caution that Mg II absorption lines can be broader than other absorption lines, hence our upper limits might not be very stringent.

We also detect several emission lines summarised in Table 4 and shown in Fig. C.1 at a common redshift of $z_{\rm em} = 0.28259 \pm 0.00005$, consistent with the absorption line redshift within errors. Their fluxes were measured through direct integration. From these measurements we derive key diagnostics of H II regions, such as extinction, SFR, and metallicity. Balmer lines are a good diagnostic for determining the level of extinction in H II regions. Their line ratio is purely determined by atomic constants. The observed 3σ limit the Hα/Hβ flux ratio of $> 1.9 \pm 0.11$ is consistent with the expected value of 2.76 for negligible extinction, assuming case B recombination. Since we have no indication otherwise, we use $A_{V,\,\mathrm{host}} = 0$ as a working hypothesis. Knowing that, the SFR is $0.037 \pm 0.002\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ as measured from Hα using the relation in Kennicutt (1998) and correcting for a Chabrier initial mass function (IMF; Chabrier et al. 2000; Förster Schreiber et al. 2009). Since Hβ is only marginally detected, we use the N2 diagnostic by Pettini & Pagel (2004) to measure the metallicity. This oxygen abundance of $12 + \log \mathrm{O/H} \geq 8.57 \pm 0.05$ corresponds to a very high metallicity of $Z = 0.8 \pm 0.1\ \mathrm{Z}_\odot$. The systematic error of this indicator is 0.18 dex Pettini & Pagel (2004).

4.2. Host Galaxy

4.2.1. Emission line diagnostics

The X-shooter spectrum of the host galaxy's nucleus (obtained 0.7 days after the GRB; see Fig. C.2) shows no absorption but a large number of emission lines at a common redshift of $z_{\mathrm{em}} = 0.28256 \pm 0.00002$, listed in Table 4. Their fluxes were measured in the same fashion as at the explosion site.

Interestingly, the Hα emission line is significantly broader than any other emission line in the spectrum, i.e. FWHM(Hα) $= 1.83 \pm 0.01$ Å but FWHM(Hβ) $= 1.22 \pm 0.05$ Å. To elucidate the origin of the broadening, we followed Chatzopoulos et al. (2011, and references therein) and assumed three distinct models: *a*) thermal broadening, *b*) single Thompson scattering of free electrons, and *c*) multiple scattering of hot free electrons. In the first scenario the proper motion of atoms leads to broadening that results in a Gaussian-shaped line profile. Since the flux of an emission line stems from the total flux of all star-forming regions, we additionally assume that there are two velocity components. The second is typical for a broad-lined region in an AGN, producing exponential line profiles ($\propto \exp^{-\Delta v/\sigma}$, where Δv is the Doppler shift from the line centre and σ is the velocity dispersion). The third describes dense media and produces Lorentzian line profiles. The top right panel in Fig. 7 shows the Hα emission line together with the best fit model. The best fit model consists of two Gaussians centred at identical wavelengths ($\lambda_1 = 8419.71 \pm 0.06$ and $\lambda_2 = 8419.79 \pm 0.02$ Å), whose FWHMs are 3.42 ± 0.03 ($\Delta v = 121.8\ \mathrm{km\,s^{-1}}$) and 1.41 ± 0.03 Å ($\Delta v = 50.2\ \mathrm{km\,s^{-1}}$), and amplitudes of 2.20 ± 0.31 and $3.21 \pm 0.19 \times 10^{-16}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, respectively. The width of the narrow component is consistent with the width of the other lines.

To check for AGN contribution, we put the integrated line measurements of Hα Hβ, N IIλ6584, and O IIIλ5007 in the BTP diagnostic plot (Fig. 15; Baldwin et al. 1981). The emission lines ratios are fully consistent with being due to star-formation. Knowing that, we use the Balmer decrements to to measure the extinction. The Balmer decrements of the narrow component between Hα, Hβ, Hγ, and Hδ are all consistent with negligible dust extinction. However, we detect no significant flux from the broader component at the position of Hβ to constrain its extinction. The inferred SFRs (computed in the same way as for the explosion site) are: $0.48 \pm 0.03\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and $> 0.33 \pm 0.05\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$ for the narrow and broad component, respectively. The N2 metallicity indicator is calibrated on integrated measurements. Therefore, we measure an integrated oxygen abundance of 8.43 ± 0.01. The metallicity of $Z = 0.55\ \mathrm{Z}_\odot$ is a bit lower than of the explosion site but they are consistent with each other within 2.5σ.

Levesque et al. (2012) carried out an independent study of the emission-line properties of the explosion site, the curved bridge connecting the galaxy's nucleus with the explosion site (Fig. 1), and the host's nucleus using Magellan's low-resolution LDSS3 spectrograph with two different position angles (PA = 50° and 141°). Their line measurements fundamentally deviate from our measurements. Specifically, their values of the radially extended emission lines Hα and the [O II] doublet are larger by 47% and < 42%, respectively,[15] of Hβ and of [O III]$\lambda\lambda$4959, 5008 by 118–184%, but that of [N III]λ6584 agrees with our measurement. At the explosion site their measurements for the [O II] doublet are by a factor of 15.8 larger, for Hα by a factor of 5.2, and [O III]λ5007 by a factor of 6 but that of [N III]λ6584 by a factor of < 2.5. The differences might be partly instrumental, because LDSS3 does not have an atmospheric dispersion corrector. Another reason is how they extracted the 1-D spectra. They used a fixed aperture of 1.″14 (the plate scale being 0.″19/px). We, in contrast, based the aperture size on the FWHM of the spectral PSF of the galaxy nucleus and the explosion site, i.e. FWHM(nucleus)=1.″34 and FWHM(GRB)=0.″86 with the plate scale being 0.″15/px. As described in 2.1, we also ensured absolute flux-calibration and checked for differential flux losses by scaling the explosion site spectrum to the brightness of the optical transient at that epoch and that of the galaxy nucleus to the brightness of the host galaxy. Levesque et al. (2012) only applied a relative flux calibration, which can be affected by (differential) flux losses. Furthermore, comparing the emission-line profiles from their spectra with their actual line measurements and uncertainties, e.g. for Hα, casts doubts on their reported values and on their inferences.

We would like to point out that two of their results are in conflict with ours, which are based on higher S/N and higher spectral-resolution data. Firstly, the fact that their spectral resolution was not sufficient lead them conclude the presence of a non-negligible amount of reddening at the galaxy's nucleus of $E(B-V) = 0.24$ mag. Our data revealed that there are two dominant populations of star-forming regions at the nucleus. After accounting for that, there are no indications for dust reddening. They also argue for a dust reddening at the explosion site ($E(B-V) = 0.31$ mag), which we can rule out. This in return significantly overestimates their SFR measurements: Levesque et al. (2012) $\gtrsim 2.7\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$, our total measurement $\gtrsim 0.8\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$. As we will show in the following section, the SED fit of the host galaxy is in full agreement with our spectroscopy results, but in conflict with Levesque et al. (2012). Secondly, our data does not show any evidence for asymmetries in the emission line profiles (see Fig. 7, C.1 and C.2), in contrast

[15] The spectral resolution in Levesque et al. (2012) is not sufficient to resolve the [O II] doublet. Their reported [O II]λ3727 should rather refer to the flux of the doublet.

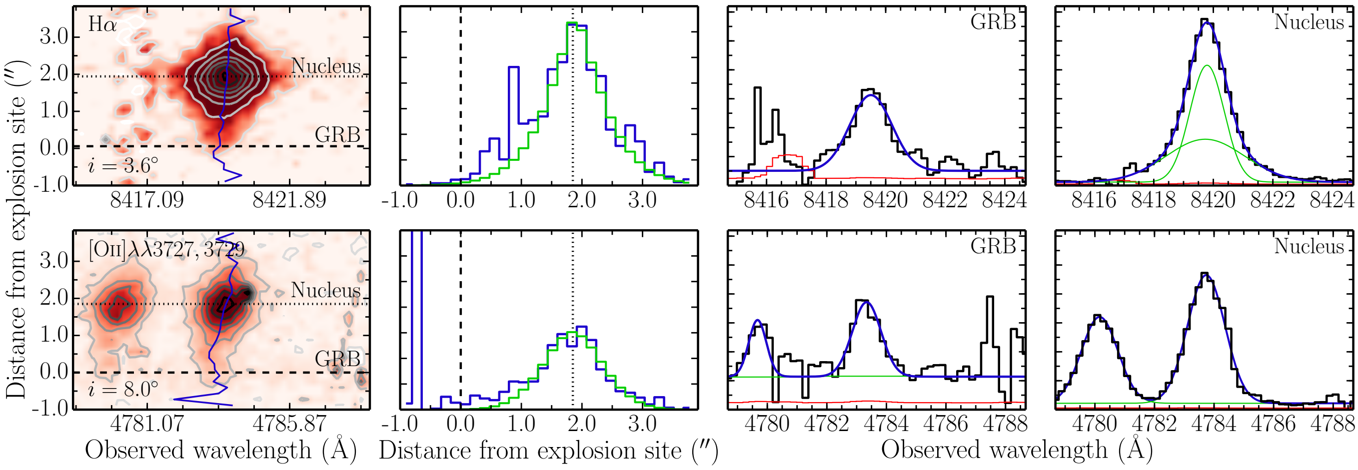

Fig. 7. Part of the rectified and wavelength-calibrated 2-D X-shooter spectrum (PA = 41°) obtained 0.72 days after the explosion (Table 1). The first column shows the 2-D profile of Hα and the [O II] doublet. The blue lines trace the position of maximum flux. The inclination angles i (defined as the angle between the major axis and a vertical line) are displayed in the lower left corner. Contour lines are overlaid to guide the eye. The cross dispersion profiles are displayed in the second column. The coding of the vertical lines is identical to that in the first column. For illustration purposes we fitted the profiles with a Sersic function, where the wings left of the centres of lines were excluded from the fit. The line profiles in dispersion direction are shown in the last two columns. The green line the fit of individual components and the blue line of the compound. At $z = 0.283$, an angular distance of $1''$ translates into a projected distance of 4.3 kpc. The error spectra in the third and forth columns are overlaid in red.

to Levesque et al. (2012). The nominal values for the skewness parameter are: 0.06–0.21 with a significance of $< 2.1\sigma$ at the explosion site and -0.03–0.1 with a significance of $< 1.7\sigma$ at the galaxy's nucleus.

4.2.2. Morphology and SED

The X-shooter spectrum from 2012 April 23 (PA = 41°; Fig. 1) reveals that the most prominent nebular lines, i.e. the [O II] doublet and Hα, extend from the galaxy's nucleus to the explosion site and slightly beyond (see Fig. 7). To obtain a better understanding of the peculiarity of the explosion site and the host morphology, we extracted their cross-dispersion profiles by fitting each row with a Gaussian (i.e. slicing the galaxy in chunks of $0\farcs15 \times 0\farcs9$, which is equivalent to an area of 0.64×3.9 kpc^2 at $z = 0.283$). The largest fluxes are recorded at the galaxy's nucleus (second column in Fig. 7), while the flux at GRB site is very low. Since both lines of sights are not affected by reddening in the host galaxy, the difference in Hα flux directly translates into a SFR difference, i.e the explosion site does not show an enhanced SFR with respect to its surroundings and the nucleus. A fit of the cross-dispersion profiles with a Sersic function (column 2 in Fig. 7) reveals an excess from the nucleus towards the GRB site. The excess in [O II] is more diffuse and extends to larger galactocentric radii. A possible explanation could be that this nebular line is in general less tightly correlated with star-formation and affected by differences in ionisation, metallicity, and dust content (for a detailed discussion see e.g. Kewley et al. 2004). We also note that the 2-D profiles are slightly slanted. We measure a velocity difference between the galaxy's nucleus and the explosion site of 7 and 22.6 km s^{-1} at Hα and [O II]λ3729, respectively. Strictly speaking these are lower limits because this X-shooter spectrum does not fully cover the nucleus.

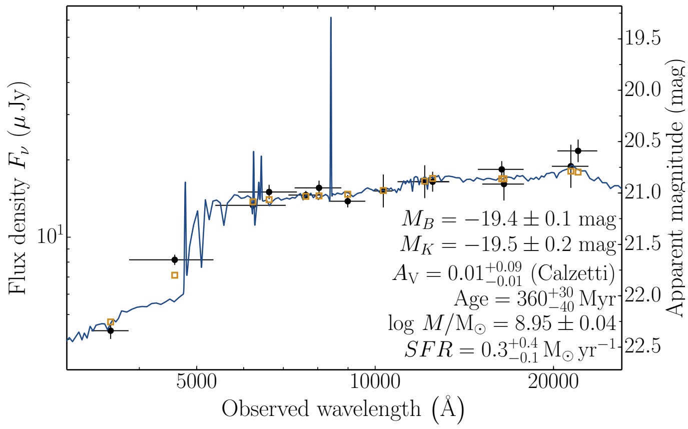

Fig. 8. Spectral energy distribution of the GRB host galaxy from 3500 to 21460 Å. The solid line displays the best fit model of the SED with `Le Phare` ($\chi^2 = 21.4$, number of filters = 14). The green points are the model predicted magnitudes.

An image of the host galaxy obtained 3.6 days after the explosion, shown in Fig. 1, reveals a curved bridge of emission connecting the transient with the host. The curved bridge was also covered by the slit of the X-shooter afterglow spectrum from 2013 April 23 (Fig. 7). Even there stars are formed at a rate that is in between that of the galaxy nucleus and the explosion site. The GRB could therefore have occurred either in a morphologically disturbed/irregular galaxy, within an interacting companion, or a spiral arm (however no counter arm is visible on the far side of the galaxy).

Table 5 lists the brightness of the GRB host galaxy from 360 to 2140 nm. We modelled the SED with `Le Phare`

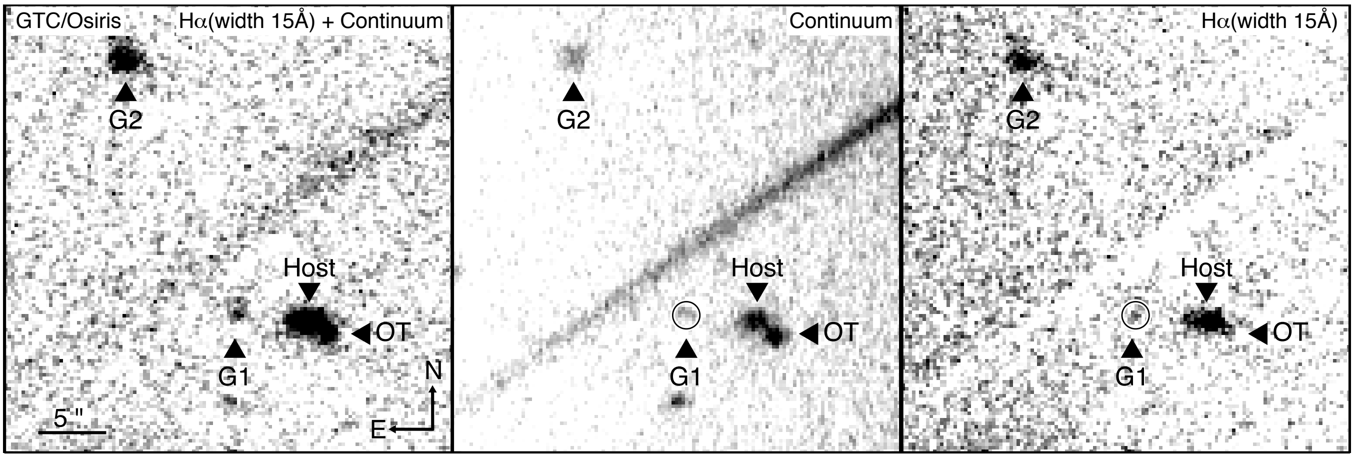

Fig. 9. Galaxy environment of GRB 120422A. The field of view has a size of $33'' \times 33''$. The left panel shows the Hα image (15 Å wide), which includes the emission line and the continuum. The middle panel shows the continuum centred at 8020 Å (6250 Å rest frame) to avoid the emission from Hα (obtained with a 513-Å-wide narrow-band filter). The right panel is the subtraction of the left and middle panel, i.e. a pure Hα image. The host and G1 are at the same redshift as the GRB (OT). The galaxy G2 is possibly at the same redshift. Their projected distances are 7.3, 28.7 and 107.8 kpc from the explosion site, respectively (see Table 6 for details). The diagonal stripes are produced by the $R = 8.24$ mag foreground star that is $79''$ NW from the explosion site.

Table 5. Brightness of the GRB host galaxy in the optical/NIR

Filter	$\lambda_{\rm center}$ (nm)	Brightness (mag)
u'	357.88	22.34 ± 0.08
g'	458.98	21.65 ± 0.05
r'	621.96	21.12 ± 0.04
R	662.30	20.99 ± 0.07
i'	764.01	21.02 ± 0.05
I	804.08	20.95 ± 0.07
z'	898.93	21.08 ± 0.06
$Y_{\rm CAHA}$	1032.28	20.98 ± 0.16
$J_{\rm CAHA}$	1212.41	20.89 ± 0.16
$J_{\rm UKIRT}$	1250.24	20.89 ± 0.10
$H_{\rm UKIRT}$	1635.35	20.77 ± 0.08
$H_{\rm CAHA}$	1649.59	20.91 ± 0.16
$K_{\rm CAHA}$	2138.97	20.74 ± 0.21
$K_{\rm UKIRT}$	2200.45	20.59 ± 0.11

Notes. The brightness was measured within a circular aperture (diameter 2.″5). The brighness was measured in $u'RI$ with NOT, in $g'r'i'z'$ with GROND, in $YJHK$ with CAHA, and in JHK with UKIRT.

(Arnouts et al. 1999; Ilbert et al. 2006),[16] using a grid of galaxy templates based on Bruzual & Charlot (2003) stellar population-synthesis models with the Chabrier IMF and a Calzetti dust attenuation curve (Calzetti et al. 2000). For a description of the galaxy templates, physical parameters of the galaxy fitting and their error estimation, we refer to Krühler et al. (2011a). To account for zeropoint offsets in the cross calibration and absolute flux scale, a systematic error contribution of 0.05 mag was added in quadrature to the uncertainty introduced by photon noise. Figure 8 displays the observed host SED and its best fit. The observed SED is best described by a low-mass, barely-extinguished star-forming galaxy with a very young starburst (see Table 7). The extracted attenuation and SFR are consistent with results from emission-line diagnostics.

[16] http://www.cfht.hawaii.edu/˜arnouts/LEPHARE

Table 6. Coordinates and distances from the optical transient to galaxies with emission consistent with Hα at $z = 0.283$ that are detected with the tuneable filters

Galaxy	R.A. (J2000)	Dec. (J2000)	projected Distance (kpc)
Host	09:07:38.5	+14:01:08.46	7.3
G1	09:07:38.9	+14:01:09.12	28.7
G2	09:07:39.4	+14:01:27.83	107.8
G3	09:07:42.9	+14:00:15.40	355.8

4.3. GRB host galaxy environment

In the previous section we briefly mentioned the possibility that the true host could be a smaller galaxy interacting/merging with the $r' = 21$ mag galaxy. To explore this scenario further, we studied the nature of other objects in the vicinity of the GRB to find evidence for a galaxy over-density or galaxy interaction. Our GTC spectrum from 2012 April 25 elucidated that object G1 is at the same redshift as the GRB ($z = 0.2831$; Fig. 1, 10, Table 6). The angular distance of 7.″1 corresponds to a projected distance of 28.7 kpc at $z = 0.283$ from the host galaxy's nucleus. Intriguingly, we detect a curved arm of emission, though not fully recovered, that connects G1 with the GRB host in our deep Gemini and Liverpool Telescope images (Fig. 1). The blue colour of the tidal arm points to recent star formation. Together with G1's blue colour, we have compelling evidence that both galaxies are interacting. This could be an indication that the arm connecting the host's nucleus with the GRB site is not a spiral arm but another tidal arm due to interaction of the $r' = 21$ mag galaxy with another galaxy. Deep *HST* observations are needed to answer this question.

To map the star-formation activity inside the host galaxy and identify more galaxies at the GRB's redshift up to distances of hundreds of kpc, we acquired a deep image with the tuneable filters (FWHM = 15 Å) centred at Hα at $z = 0.283$ with the GTC 25.5 days after the GRB. Figure 9 shows a $33'' \times 33''$-wide post stamp. The left panel was obtained with the 15 Å wide tuneable filter, i.e. it contains the emission from the Hα line and the continuum emission. The continuum, displayed in the middle panel, was imaged with a broad-band filter centred at 8020 Å (width 513 Å) that does not cover Hα. The SN continuum is not highly variable, neither in the spectral range of the broadband filter nor at Hα (Fig. 4); the same is true for the host galaxy (Fig. 8). Hence, the difference image of both observations shows the pure Hα emission (right panel).

We detect four galaxy candidates that have emission consistent with Hα at $z = 0.283$ (Fig. 9, Table 6). We identify the closest one, located at 7.8 kpc of the GRB, as the host. The galaxy G1 (23 kpc from the centre of the host galaxy), already identified with the GTC spectrum from 25 April, is a satellite galaxy. The galaxies G2 and G3 (not shown in Fig. 9) could be members of the same galaxy group, however a spectrum or an additional observation tuned to the wavelength of another emission line are needed for confirmation.

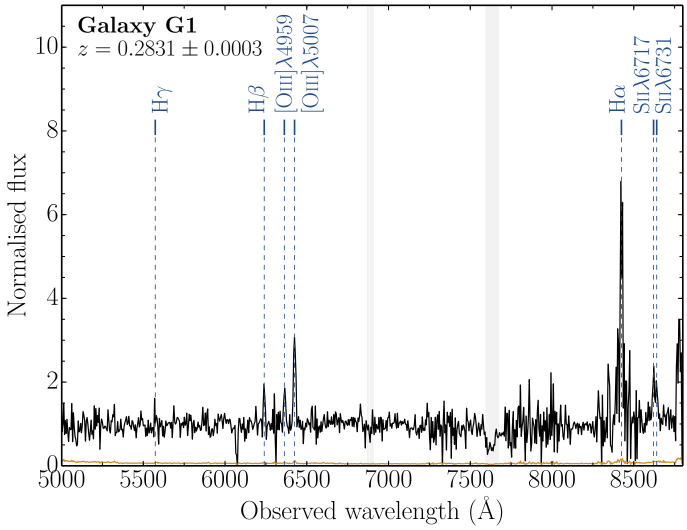

Fig. 10. Normalised spectrum of galaxy G1 (see Fig. 9), obtained with GTC/Osiris 3.6 days after the GRB. Several emission lines are detected at $z = 0.2831$. Hα is partly blended with a sky emission line. The error spectrum is shown in orange. The positions of telluric bands are are highlighted by grey-shaded areas.

5. Discussion

5.1. SN 2012bz

In Sect. 3.1 and 3.3, we presented the properties of the GRB-SN. The initial UV/optical emission until 10 ks is dominated by the thermal emission of the cooling stellar envelope after the shock break-out. About 1.4 hours after the GRB, the stellar envelope had a temperature of 16 eV and a radius of 7×10^{13} cm. By modelling the radioactively powered light curve we obtained: $M_{\rm Ni} = 0.40$ M$_\odot$, $M_{\rm ej} = 4.72$ M$_\odot$ and $E_{\rm k} = 3.29 \times 10^{52}$ erg, and when the NIR emission is included, the nickel and ejecta masses to increased by 45 and 25%, respectively, and the kinetic energy by 25%. These values are among the highest recorded values for GRB-SNe (Cano 2013). We computed the intrinsic V-band luminosity through direct integration over the SN spectrum. SN 2012bz has a absolute V-band magnitude of -19.7 mag, making it 0.3 mag more luminous than SN 1998bw. The phenomenological modelling of the SN light curve gave a similar value. In the r' band that overlaps with the rest-frame V band we inferred the SN to be 0.3 mag brighter than SN 1998bw but a slightly faster evolution. In the following we will discuss the SN properties in the context of other GRB-SNe.

5.1.1. SN 2012bz in the context of other GRB-SNe

Figure 11 shows the comparison of SN 2012bz at two different phases for which simultaneous spectra of SNe 1998bw, 2006aj and 2010bh are available, all of which accompanied low-L GRBs (Patat et al. 2001; Pian et al. 2006; Bufano et al. 2012). Overall, the spectra are very similar and show the same features, although line strengths and expansion velocities vary from object to object. We have illustrated this by annotating the main features as they have been identified in the past (e.g. Patat et al. 2001): Fe II, usually visible between 4500–5000 Å; Si II, around 5600–6100 Å; the Ca II IR triplet (that for SN 2012bz is in a noisy part of the spectrum between the VIS and the NIR arms; see lower panel); and possibly He I, at around 5500 Å (e.g. Bufano et al. 2012). We stress that these SNe have very large explosion velocities and that their broad lines are likely the result of blending, hampering the identification of the dominating line species producing the absorption feature.

Nevertheless, spectra of different GRB-SNe displayed in Fig. 11 are remarkably similar, reinforcing the idea that the nature of these blends, whatever it is, is the same for all GRB-SNe, pointing towards similar explosions. Differences do however exist in the expansion velocities (see Fig. 5). The spectra are displayed in an ‘expansion velocity sequence’ going from the ‘fastest’ (SN 2010bh; see also the discussion in Chornock et al. 2010; Bufano et al. 2012) to the ‘slowest’ (SN 2006aj). This is at least true for the Fe II and Si II lines and, in that respect, SN 2012bz seems intermediate and more similar to SN 1998bw. The Ca IR triplet shows a different velocity behaviour, not correlated with the one determined by the other elements, and SN 1998bw is clearly faster at all phases.

It is interesting to point out that the notch that has been possibly identified as He I by Bufano et al. (2012) (Fig. 11 panel a) is also visible in SN 2012bz, and as a matter of fact in most optical GRB-SNe spectra with sufficient S/N to the left of the main Si II trough. A powerful diagnostic to test the presence of He I is NIR spectroscopy (Patat et al. 2001; Bufano et al. 2012). Our X-shooter NIR spectra are unfortunately of low S/N and for this reason we focus our analysis only on the one obtained at maximum light (Fig. 11 lower panel). Still, however, this spectrum is dominated by a weak continuum, while most prominent features are located in unfavourable regions (the error spectrum is displayed). For comparison, we have also plotted an X-shooter spectrum of SN 2010bh obtained at a similar phase (Bufano et al. 2012). SN 1998bw does not have a contemporaneous spectrum but we show the one obtained at $T_0 + 33$ day, where the identified features are more clearly visible (Patat et al. 2001). Both the locations where one would expect to see He Iλ10830 or C I$\lambda\lambda$10695, 16890 are located in very noisy atmospheric regions of our spectra, at the redshift of SN 2012bz, preventing us from drawing any meaningful conclusion.

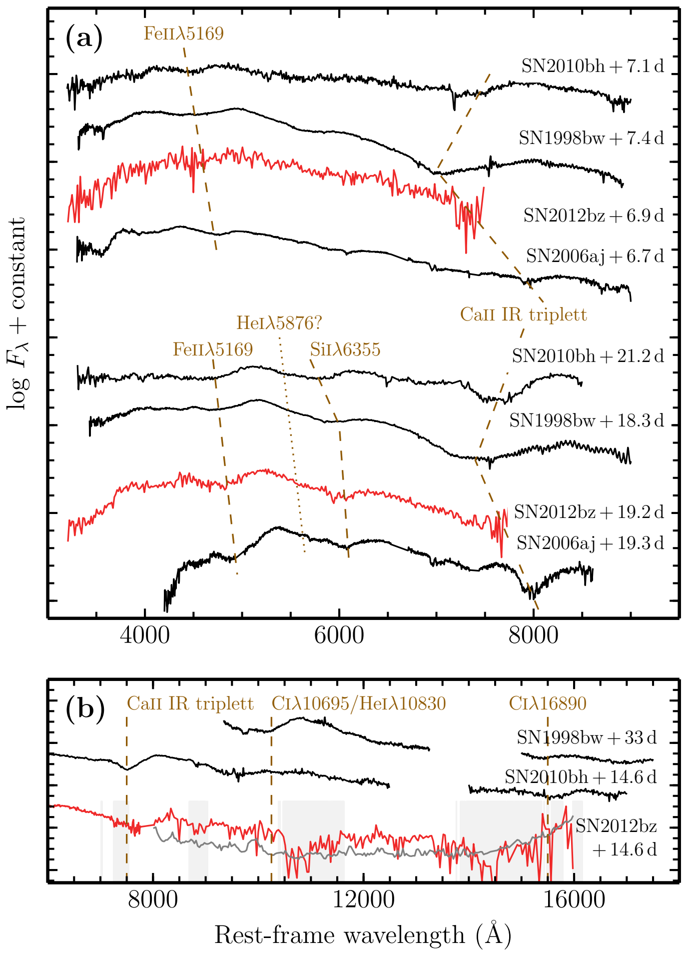

Fig. 11. (a) Comparison of SN 2012bz (red) to that of low-L GRB SNe (black) at two different phases, ~ 7 and ~ 20 days past explosion, respectively. All comparisons are made in the rest frame. The dashed lines connect the approximate minima for the Fe II and Si II features and the spectra are shown in an expansion velocity sequence from the fastest (SN 2010bh) to the slowest (SN 2006aj). A less significant (but real) feature that has been proposed to be He I is also identified. (b) NIR arm of the X-shooter spectrum of SN 2012bz at maximum light (red). The thin grey line is the error spectrum. The Ca II IR triplet at the redshift of SN 2012bz is located between the VIS and NIR arms. For comparison NIR spectra of SN 1998bw and SN 2010bh are shown along with identification of the most prominent lines (Patat et al. 2001; Bufano et al. 2012). Unfortunately these features fall in unfavourable noisy regions of our spectrum.Positions of atmospheric features (shifted to the redshift of GRB 120422A) are highlighted by the grey-shaded areas.

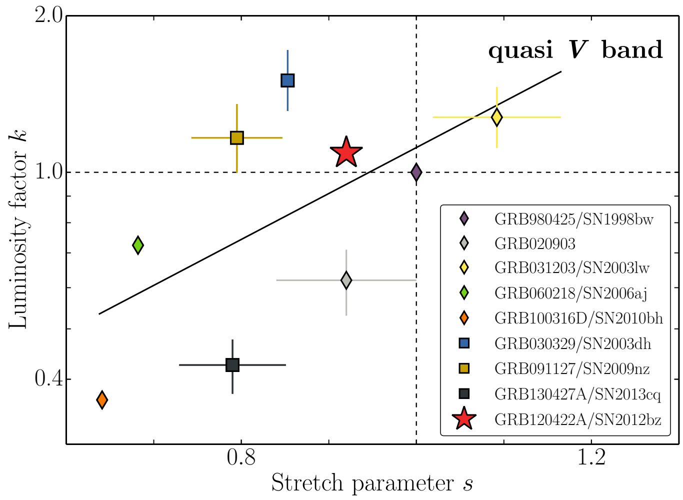

Fig. 12. The SN luminosity factor k (peak luminosity in units of SN 1998bw's peak luminosity) vs. the stretch factor s (time dilation vs. SN 1998bw's peak time) in the quasi rest-frame V band. Quasi rest-frame V band means that the observed bandpass partially overlaps with the rest-frame V-band. Low-L GRBs are displayed by diamonds, high-L GRBs by squares, and the intermediate-L GRB 120422A by a star. **References**: GRBs 020903, 030329, 031203, 060218 (Ferrero et al. 2009), GRBs 091127 and 100316D (Kann in priv. comm.), and GRB 130427A (here).

5.1.2. A Philips-type relation for GRB-SNe?

GRB-SN spectroscopy is in most cases limited to $z \lesssim 0.3$, the redshift domain that is observationally dominated by low-L GRBs. At higher redshifts, the detection of a GRB-SNe mostly depends on the detection of late red bumps, that are modelled with a SN1998bw template. In the past years, the sample of GRBs with detected late red bumps has been substantially increased (Ferrero et al. 2006; Thöne et al. 2011; Cano 2013). We will use these samples to compare the luminosity factor k and the stretch factor s of low- and high-L GRBs. Among these, we only select those with meaningful values, i.e. GRB-SN that were ranked better than "C" in Hjorth & Bloom (2012).[17] Furthermore, most values were only obtained in one band, mostly in the observed R band. Since GRB-SNe have up to now been identified between $z = 0.0085$ and $z \simeq 1$, the observed R band probes different regions in the rest-frame. GRB-SNe emit most of its energy in the rest-frame V band. Therefore, we only use those values where the observed bandpass partly overlaps with the rest-frame V band (in the following called quasi V band).

Figure 12 displays the parameter space of the nine GRB-SNe that fulfilled both criteria. Supernovae of low-L and high-L GRBs occupy the same parameter space. Intriguingly, there is a trend between the luminosity and the stretch factor.[18] This is in line with recent findings by Hjorth (2013), who independently reported on a correlation between the peak magnitude and the width of the peak. To estimate the correlation degree and significance we applied a Monte Carlo technique. In this method, every data point is represented by a 2-D Gaussian, where the centre of peaks in each dimension are the parameter estimates, and the corresponding 1σ errors are the width of the distributions. From these, we construct 30000 resamples of the observed data sets, each of which is obtained by a random sampling with replacement from the original data set. Note, SN 1998bw was excluded since it is the

[17] For an updated list see:
http://www.dark-cosmology.dk/GRBSN/GRB-SN_Table.html .
[18] Such a correlation was searched for GRB-SNe in Ferrero et al. (2006) and Cano et al. (2011a), but not found because all data were used disregarding which rest-frame waveband they probed, or on much less data that also did not probe the same rest-frame waveband (Stanek et al. 2005).

reference value. For each of these data sets we do a linear regression fit, using the model $\log_{10} k = A \times s + B$, and determine the correlation coefficients. The best fit values and their uncertainties are given by the centre and the width of the distribution functions. The best fit values are: $A = 0.89 \pm 0.24$, $B = -0.84 \pm 0.19$. The Pearson's correlation coefficient, Spearman's rank, and Kendal's τ give significances of $\sim 1.3\sigma$. Despite the correlation being statistically not significant, the trend is similar to the Phillips relation (Phillips 1993) that builds the foundation for using Type Ia SNe as standard candles in cosmology.

The degree of correlation is affected by several systematics. First of all, none of the displayed k, s values represent the true rest-frame V band. To obtain the rest-frame V band values a more sophisticated approach is needed, which is beyond the scope of this paper. Systematic differences can arise from the fact that all GRB-SNe are broad-lined Type Ic SNe, but the evolution and the strength of absorption features depend on the specific GRB-SN (see Fig. 5, 11), which we think could be responsible for $\sim 20\%$ of the observed scatter. Uncertainties in the line-of-sight extinction are the second largest source of error affecting k but not s. For instance, the afterglow data of GRB 020903 are not good enough to build a SED for estimating the line-of-sight extinction. The extinction towards GRB 060218/SN 2006aj and GRB 100316D/SN 2010dh are very high and uncertain (Cano et al. 2011a; Bufano et al. 2012; Olivares E. et al. 2012). Furthermore, there are different approaches how a 1998bw-template light curve for specific band is constructed. Specifically, for GRB120422A we measure a difference of 0.10 mag in the observed r'-band peak magnitude between the methods by Zeh et al. (2004) and Cano (2013). The host contribution was taken into account either by image subtraction, subtraction of the nominal host flux, or by adding the host magnitude as a free parameter to the light curve fit for all GRB-SNe, except for GRB 130427A. Last but not least, the SN fit depends on how well the afterglow component is modelled. This affects k as well as s.

5.2. The afterglow of GRB 120422A

Our analysis in Sect. 3.2 reveals: *i*) the optical (redward of B band) and the NIR emission of the transient accompanying GRB 120422A to be afterglow-dominated between ~ 2 and 86 ks, *ii*) the X-ray emission to be consistent with synchrotron radiation at all times (except for some small deviations within the first 200 s after the burst; Starling et al. 2012), *iii*) an initial Lorentz factor of $\Gamma_0 \sim 60$, *iv*) an afterglow peak luminosity-density of $\lesssim 2 \times 10^{30}$ erg s^{-1} Hz^{-1}, and *v*) a constant-density circumburst medium. Like in the SN discussion, we will put the afterglow in context with low and high-L GRBs.

Finding a constant-density medium around a massive star is not so surprising. Schulze et al. (2011) showed that most GRBs are found in constant-density-medium environments. Simulations by van Marle et al. (2006) showed that a complex mass-loss history or differences in the ram pressure can stall a free-stellar-wind density profile closer to the progenitor star and make the disturbed density profile look like a constant density medium.

Measurements of the initial Lorentz factor are limited to a small number of bursts with rapid follow-up. Typical values are about few hundred for high-L GRBs (Molinari et al. 2007; Ferrero et al. 2009; Greiner et al. 2009; Perley et al. 2011). For low-L GRBs, measurements exists for 060218 (Soderberg et al. 2006a) and 100316D (Margutti et al. 2013). For both bursts, the inferred Lorentz factor were $\Gamma = 1.5$–2.3 at 1 (GRB 100316D) and 5 days (GRB 060218) after the burst. These measurements were obtained when the blast-wave had already decelerated. According to Zhang & Mészáros (2004, and references therein), a blast-wave's Lorentz factor evolves as $\Gamma \propto t^{-3/8}$ and $\Gamma \propto t^{-1/4}$ for a constant-density and a free-stellar-wind ambient density profile during the deceleration phase, respectively. Given the time when the Lorentz factors were obtained, the initial Lorentz factors were at most one order of magnitude larger, still smaller than that of GRB 120422A. This re-assures us in the identification of this phase transition and also illustrates the decrease in the blast-wave's velocity from high- to low-L GRBs.

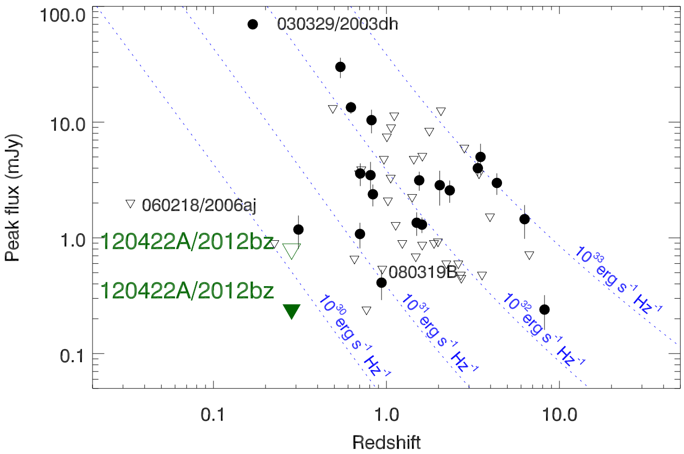

Fig. 13. Peak flux-density measured at sub-mm/mm wavelengths vs. redshift. Triangles indicate 3σ detection limits. The deepest observed limit on the peak flux-density of GRB 120422A is displayed by the filled green triangle, while the limit from the SED modelling is highlighted by the empty green triangle. Dotted lines display flux-density levels for equal luminosity at varying redshifts. Several interesting bursts are highlighted in the figure: the high-L GRBs 030329 and 080319B, the low-L GRB 060218, and the short GRB 050509B, i.e. a burst that originated from the coalescence of a binary system of compact objects. Figure adapted from de Ugarte Postigo et al. (2012b).

As mentioned in Sect. 3.2.3, the peak of an afterglow synchrotron spectrum crosses the cm to sub-mm range within the first week. During the first week an afterglow can also exhibit variability that can affect the peak flux and value of the injection frequency. Several sub-mm observations during the first week after the burst can be used as proxy for the peak luminosity without the need for modelling the broad-band afterglow (de Ugarte Postigo et al. 2012b). Figure 13 displays the inferred sub-mm peak fluxes as a function of redshift. The observed limit on GRB 120422A's peak flux-density from the sub-mm/mm observations and the limit from the SED modelling point to faint afterglow. The limit of $\lesssim 10^{30}$ erg s^{-1} Hz^{-1} is exceptionally deep for high-L GRBs. For example, the afterglow of GRB 030329, a burst with spectroscopically confirmed SN and $E_{\rm iso} > 10^{51}$ erg, had a $\sim$ 200-times larger peak luminosity density and the afterglow of GRB 080319B, a

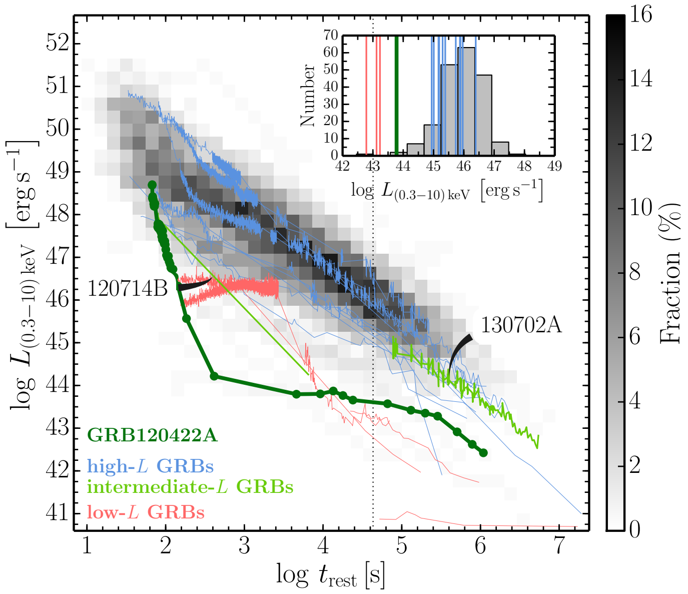

Fig. 14. X-ray light curves of low, intermediate and high-L SN-GRBs. Overlaid is the evolution of the observed luminosity distribution of 258 long *Swift* GRBs for which a SN search was not feasible or unsuccessful (i.e. GRBs 060505 and 060614) that were discovered between December 2004 and June 2013. The colour table on the right side translates a grey shade at a given luminosity and time into a fraction of bursts. The inset displays the observed luminosity distribution at 0.5 days (dotted vertical line). The vertical lines in the inset show the luminosity of intermediate-L GRB 120422A and the low-L GRBs 031203, 060218 and 100316D.

burst with photometric evidence for a SN (Tanvir et al. 2010), was about ~ 20-times more luminous than 120422A. Intriguingly, the peak luminosity density is in the expected range of low-L GRBs, such as GRB 060218.

Current sub-mm observations are limited to a small number of GRBs ($\sim 5\%$ of all GRBs) and have only been successful in detecting bright afterglows. The number of *Swift* GRBs with measured redshift is $\sim 27\%$, i.e. ~ 5-times larger than the sub-mm/radio recovery rate and almost all GRBs with redshift information have a detected X-ray afterglow. de Ugarte Postigo et al. (2012b) reported on the presence of a correlation between the sub-mm flux density and the X-ray flux density at 0.5 days, as expected if they are co-spatial. Hence, we can re-address the question on the faintness of GRB 120422A's afterglow by exploring the X-ray luminosity distribution.

We download the 0.3–10-keV light curves of long *Swift* GRBs (i.e. $T_{90} \geq 2$ s) with detected X-ray afterglow (requiring at least two X-ray detections) and known redshift that were discovered between December 2004 and June 2013 from the *Swift* Burst Analyser (Evans et al. 2010). Because of the small number of low-L GRBs in the *Swift* sample, we include all pre-*Swift*-era GRBs with detected supernova, which are mostly low-L GRBs. We retrieve their light curves from the *BeppoSAX* GRB Afterglow Database (de Pasquale et al. 2006; Gendre et al. 2006).[19] The differences in the observed bandpasses were taken into account to compute the X-ray luminosity in the 0.3–10-keV bandpass.

[19] http://www.asdc.asi.it/GRBase/

In total, $\gtrsim 270$ GRBs fulfil both criteria. Following Hogg et al. (2002) and assuming a top-hat response function, the luminosity between 0.3 and 10 keV is given by

$$L_{(0.3-10)\,\mathrm{keV}} = 4\pi\, d_L^2\,(z)\,(1+z)^{\beta-1}\,F_{(0.3-10)\,\mathrm{keV}},$$

where d_L is the luminosity distance and β is the spectral slope. The Burst Analyser provides information on the spectral slope for each data point, inferred from hardness ratio (Evans et al. 2010). Sometimes the given slope is highly variable or has unphysical values (for limitations of the Burst Analyser see Evans et al. 2010), especially at late times ($t > 1000$ s) when statistics are poor. To minimise the impact of such deviations, we set the spectral slope to the median late-time spectral slope (i.e. $t > 1000$ s) if deviations are $< 3\sigma$ and if the slope is larger than 4. For pre-*Swift* GRBs only the time-average spectral slope is available. Next we resampled the rest-frame X-ray light-curves to a grid defined by the observed luminosities of and the time interval spanned by all X-ray afterglows, and interpolated between adjacent data points in case of orbit gaps. The resulting luminosity distribution as a function of rest-frame time is shown in Fig. 14 (the grey shaded area). Highlighted in this plot are GRBs with detected SNe, colour-coded according to their time-averaged γ-ray luminosity.

The inset in Fig. 14 shows the luminosity distribution of 196 X-ray afterglows at 0.5 days after the burst. High-L GRBs with detected SNe occupy the same parameter space like all high-L for which no SN search was feasible. This supports the discovery made by Xu et al. (2013) that even bursts with the largest energy releases during the prompt emission are accompanied by SNe (see also Tanvir et al. 2010). Low- and intermediate-L GRBs lie at the very faint end of the luminosity distribution. Specifically, GRB 120422A is 2.1 dex fainter than the mean value, while the afterglows of the brightest low-L GRBs are by a factor of only a few less luminous than that of GRB 120422A.

5.3. The host galaxy and galaxy environment

Our analysis in Sect. 4 revealed that *i*) the extinction at the explosion site as well as the galaxy nucleus is negligible, *ii*) there are two populations of H II regions in the nucleus, *iii*) the GRB appears to have not occurred in a region of enhanced SFR, *iv*) the metallicities of the nucleus and the explosion site are high and identical to within errors, *v*) the host galaxy is interacting with a galaxy at a projected distance of 23 kpc, and *vi*) the host is possibly embedded in a galaxy group. First we will discuss the GRB environment in the context of all GRBs, then the host galaxy and finally the host environment.

The GRB environment appears to be rather average. The lower limit on the Mg II column density of $\log N > 13.8$ is ~ 1 dex lower than that of an average GRB environment (Christensen et al. 2011), but such a low column density was reported for other GRBs before: 050922C $\log N = 14.6 \pm 0.3$ (Piranomonte et al. 2008), 121019B $\log N = 13.43^{+0.08}_{-0.10}$ (Sparre et al. 2011), and even lower GRBs 070125: $\log N = 12.96^{+0.12}_{-0.18}$ (De Cia et al. 2011) and 071003: $\log N > 12.6$ (Perley et al. 2008). To quantify the integrated absorption-line strength of the interstellar medium in GRB host galaxies, de Ugarte Postigo et al. (2012a) introduced the line-strength parameter (LSP) that

Table 7. Properties of the host galaxy and GRB hosts at $z < 1.5$

Parameter	Host	GHostS	TOUGH
Sample size		74	20
Redshift	0.28256	$0.78^{+0.23}_{-0.33}$	$0.83^{+0.25}_{-0.44}$
$M_{\mathrm{UV,est}}$ (mag)	-18.0	$< -18.6 \pm 1.2$	$< -18.4 \pm 1.4$
$M_{K_{\mathrm{s}},\mathrm{est}}$ (mag)	-19.8	$< -20.6^{+0.6}_{-0.9}$	$< -19.4^{+0.6}_{-0.5}$
$M_{B,\mathrm{SED}}$ (mag)	-19.4 ± 0.1	$-20.5^{+1.1}_{-1.0}$	...
$M_{K_{\mathrm{s}},\mathrm{SED}}$ (mag)	-19.5 ± 0.2	$-20.2^{+1.0}_{-0.9}$	...
A_V (mag)	$0.01^{+0.09}_{-0.01}$	$0.6^{+0.6}_{-0.2}$	...
$\log M_\star (\mathrm{M}_\odot)$	8.95 ± 0.04	9.3 ± 0.5	...
Age (Myr)	360^{+30}_{-40}	1119^{+896}_{-325}	...
SFR ($\mathrm{M}_\odot\,\mathrm{yr}^{-1}$)	$0.3^{+0.4}_{-0.1}$	$2.4^{+4.0}_{-1.7}$	...
Z ($\mathrm{Z}_\odot$)	0.6	$0.5^{+0.2}_{-0.1}$	...
Offset (kpc)	7.3	$1.9^{+1.2}_{-1.3}$	...

Notes. Host properties of 120422A, and the median values of GRB hosts as compiled in the GHostS database (date: 2013 December 3) and of the homogeneous, optically unbiased TOUGH survey (Hjorth et al. 2012, incl. results from Schulze et al. in prep.). The errors of the comparison samples indicate the distance from the median values to the 25 and 75% percentiles. The age represents the age of the starburst. The stellar mass of GRB 120422A's host was calculated assuming the Chabrier IMF. The UV and K_{s} luminosities, marked by 'est' were computed using the method in Schulze et al. (in prep.) and Laskar et al. (2011), respectively. Measurements designated with 'SED' were obtained from SED fitting. The GRB offsets of the sub-set of bursts in the GHostS sample are compiled in Bloom et al. (2002) and the age distribution and results from SED fitting for the GHost sample were taken from Savaglio et al. (2009).

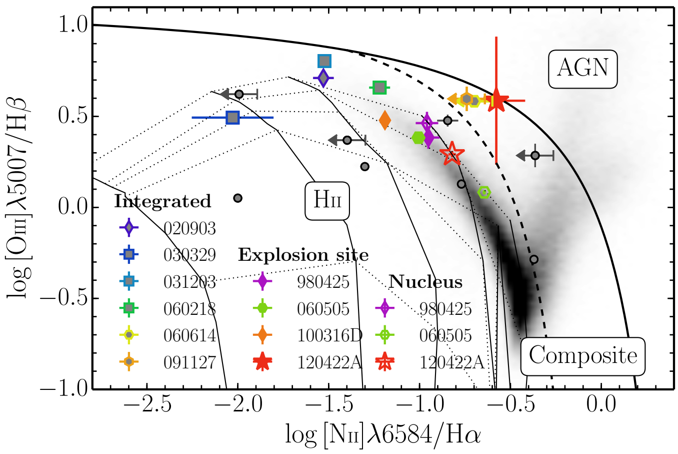

Fig. 15. Emission-line ratios for low-L ($\Diamond$) and high-L ($\square$) GRB hosts and explosion sites. Long GRBs for which a SN search was not feasible are shown as circles. Limits are signified by arrows. For comparison, the emission-line ratios are overlaid for a wide population of field galaxies from the SDSS DR9 (Ahn et al. 2012) sample as density plot. Among these data we selected those whose emission lines were detected at $> 5\sigma$ c.l. The discerning line between star-formation and AGN-dominated galaxies is shown as thick solid line and was taken from Kewley et al. (2001) and the region of composite galaxies is encircled by the thick solid the thick dashed lines (Kauffmann et al. 2003). Evolutionary models, calculated by Dopita et al. (2006), that link emission-line regions at ages from 0.1 to 5 Myr (shown as dotted lines; ages: 0.1, 1, 2, 3, and 4 Myr with the youngest stellar populations having the highest [O III]/Hβ line ratios) and different metallicities (shown as thin solid lines; $Z = 0.05$, 0.2, 0.5, 1.0, and 2.0 $Z_\odot$; metallicity increases from left to right) are displayed. Error are shown, if available. In some cases these are smaller than the size of the respective plot symbol. Figure adapted from Christensen et al. (2008).

References. Della Valle et al. (2006a): the SN-less GRB 060614; Hammer et al. (2006): 980425, Han et al. (2010): 990712, 020903, and 030329; Levesque et al. (2010a): 991208, 010921, 050826, and 070612; Levesque et al. (2010b): 020819B; Thöne et al. (2008): the SN-less GRB 060505; Wiersema et al. (2007): 060218; Krühler et al. (2012): 080605A; Vergani et al. (2011): 091127; Levesque et al. (2011): 100316D

is derived from detected absorption lines. The observed *LSP* of -0.15 ± 0.40 is small, but considering the large error, the value is consistent with the mean for GRB environments. In contrast to that, the high metallicity is exceptional (see Christensen et al. 2008; Thöne et al. 2008; Levesque et al. 2011), though the dark GRB 020819A occurred in an even higher-metallicity environment (Levesque et al. 2010b). Moreover, the negligible reddening in conjunction with the very high metallicity is remarkable. A possible reason for this high metallicity could be the limited spatial resolution. For example, based on *HST* observations Fynbo et al. (2000) showed that the stellar cluster, of which GRB 980425A's progenitor was part, was very compact (the radius being 2.25 pc) and faint, and at lower spatial resolution it would merge with a much brighter Wolf-Rayet star hosting complex 800 pc away. In contrast, the extracted X-shooter spectrum averages over an area of 0.64×3.9 kpc^2. We also note that emission-line metallicities average over all star-forming regions along the line-of-sight, not exclusively the GRB explosion site. On the other hand, if the explosion site has indeed such a high metallicity, this might challenge current GRB progenitor models that predict a low-Z cut-off (Woosley 2012, and references therein).

To address this peculiarity further, we compare the [O III]/Hβ vs [N II]/Hα line ratios with those of other GRB hosts (see Fig. 15). In addition, we distinguish between spatially-resolved and integrated line measurements. The emission-line ratio of the host's nucleus is not different from other GRB hosts. All hosts are located in the region that is dominated by H II regions. Compared to models by Dopita et al. (2006), the observed line ratios always point stellar populations with an age of a few million years and metallicities between 0.05 and 2 $Z_\odot$, in contrast to the bulk of emission-line galaxies in the SDSS DR9 (Ahn et al. 2012). GRB 120422A's host is among the most metal-rich GRB hosts. The large uncertainties in the line measurements of the explosion site do not allow to draw a firm conclusion on its peculiarity.

Comparing the integrated host properties with GRB samples is not straightforward. Most samples are heterogeneous and biased towards a particular GRB population, e.g. GRBs with negligible reddening or bright afterglows. On the other hand, optically unbiased samples are limited to observations in a few bands, from which only a few host properties can be extracted. Keeping these limitations in mind, we compare 120422A's host with the GHostS database, built by Savaglio et al. (2009), that contains well-sampled multi-band SEDs and host spectra for a larger number of hosts, and the optically-unbiased, homogeneous GRB host (TOUGH) sample by Hjorth et al. (2012), which is in most cases limited to observations in R and K_s bands. Based on recent findings by Perley et al. (2013b) that GRB hosts at $z < 1.5$ are bluer and significantly less massive than higher redshifts, we limit the comparison to hosts at $z < 1.5$.

Table 7 lists the host properties of 120422A and the median values for both comparison samples. In context of the GHostS sample, GRB 120422A's host is in the lower half of the luminosity, mass and SFR distribution. Only its very low extinction (0.5 mag less than the GHostS median) in combination with high metallicity are peculiar. We caution that the completeness of both properties is very low. Another peculiarity is the exceptional large distance between the explosion site and the galaxy's nucleus. The offset of 7.3 kpc is among the largest values reported in Bloom et al. (2002). Based on the optically-unbiased TOUGH sample, a slightly different picture can be drawn. Since only observations in two filters are available for most hosts, we assume that the rest-frame NIR and UV can be approximated by power laws, similar to the approaches in Laskar et al. (2011) and in Schulze et al. (in prep.). We measure a UV luminosity at 1700 Å of −18.0 mag and a K_s-band luminosity of −19.8 mag (see Table 7). These values are consistent with the ensemble median values.

Observations with the tuneable filters revealed that host is interacting with another galaxy that is at a projected distance of 23 kpc from GRB 120422A host galaxy's nucleus and that there are possibly two further star-forming galaxies at the same redshift within ~ 360 kpc. In general, little is known about the galaxy environments of GRB host galaxies. Several GRB fields show an increased galaxy density, e.g. GRBs 000301C, 000926 (Fynbo et al. 2002), 011211 (Fynbo et al. 2003), 021004 and 030226 (Jakobsson et al. 2005), 030115 (Levan et al. 2006), and GRB 050820A (Chen 2012), but nearest burst, GRB 980425, does not (Foley et al. 2006). The comparison is also limited due to the lack of information for SN fields.

5.4. The missing link between low- and high-L GRBs

The division between low- and high-L GRBs is not entirely operational. Both populations have very distinct properties. Low-L GRBs are thought to be driven by shock breakouts, producing (quasi-)spherical explosions whose γ-ray light curves are smooth and single-peaked (Campana et al. 2006; Starling et al. 2011), spectra that can have peak energies of only a few keV (e.g. Campana et al. 2006; Starling et al. 2011, but see Kaneko2007a), and mildly relativistic outflows ($\Gamma < 10$; e.g. Soderberg et al. 2006a Margutti et al. 2013). In contrast, high-L GRBs are powered by ultra-relativistic collimated outflows with Lorentz factors of a few hundred (Molinari et al. 2007; Ferrero et al. 2009; Greiner et al. 2009; Perley et al. 2011), and γ-ray light curves that can exhibit variability on the milli-second domain (Bhat et al. 2012). The rate of low-L GRBs in the nearby Universe exceeds that of high-L GRBs by a factor of 101000 (Pian et al. 2006; Guetta & Della Valle 2007; Virgili et al. 2009; Wanderman & Piran 2010). However, a recent work by Lazzati et al. (2012) based on relativistic jet simulations proposed a non-uniform distribution of the central engine's on-time to account for the differences.

GRB 120422A is one of the very few examples of intermediate-luminosity GRBs. Its γ-ray light curve exhibits an initial spike (starting at $T_0 - 3$ s and ending at $\sim T_0 + 20$ s; Barthelmy et al. 2012) followed by a weaker and softer extended component (starting at $T_0 + 45$ s and ending at to $T_0 + 65$ s; Barthelmy et al. 2012), as observed in other high-L GRBs before (Bostancı et al. 2013). In addition, the X-ray emission is not dominated by thermal emission from the cooling photosphere after the shock breakout, like the low-L GRBs 060218 and 100316D (Campana et al. 2006; Nakar & Sari 2012). In contrast, the properties of the longer-lasting transient accompanying the GRB point in a different direction. The blast-wave had a very low initial Lorentz factor of $\Gamma_0 \sim 60$ and the produced afterglow had an unprecedentedly low peak luminosity of $L_{\nu,\,\max} \lesssim 2 \times 10^{30}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$ for a high-L GRB. Thanks to the weak afterglow, the signature of the shock break-out was for the first time detected for a non-low-L GRB.

The failed-jet model predicts high-L GRBs to transition into low-L bursts as the jet produced by the central engine gets weaker, e.g. because of a lower kinetic energy in the outflow, a central engine that is active of a shorter period, or a less collimated outflow (Bromberg et al. 2011; Lazzati et al. 2012). According to this model, the weaker a jet, the more it gets decelerated in the stellar envelope until it is choked. Examples for choked jets are the Type Ib/c SNe 2002ap, 2012au (Soderberg et al. 2006b; Milisavljevic et al. 2013; Margutti et al. 2013) and GRB 100316D whose jet barely broke through the stellar cocoon (Margutti et al. 2013). The fact that we do detect the thermal emission from the cooling photosphere after the shock break-out raises the questions of how much energy GRB 120422A's jet already transferred into the stellar envelope and how much more energy it could lose before getting choked. As coined by Hjorth (2013), GRB 120422A is indeed a transition object between shock-break-out driven low-L and high-L GRBs that are powered by ultra-relativistic jets.

To fully connect GRBs of low and high luminosities, it has to be shown that even the most luminous bursts ($L_{\rm iso} \sim 10^{54}$ $\mathrm{erg\,s^{-1}}$) are accompanied by SNe. These very energetic bursts have however been found at redshifts where SN searches are getting unfeasible, i.e. $z \gtrsim 1$. Serendipitously, one of the most energetic bursts, GRB 130427A, occurred at $z = 0.34$ (Perley et al. 2013b; Xu et al. 2013). During its prompt γ-ray emission that had a duration of $T_{90} = 276\,\mathrm{s}$, this burst released 8.1×10^{53} erg; Maselli et al. 2013). This translates into a time-averaged γ-ray luminosity of $L_{\rm iso} \sim 10^{51.6}$ $\mathrm{erg\,s^{-1}}$. Thanks to its low redshift, an accompanying broad-lined Type Ic SN was spectroscopically detected with properties similar to those of low-L GRBs (Xu et al. 2013, see also Tanvir et al. 2010, who reported on the photometric SN discovery for an almost 1 dex more luminous GRB). In addition, Maselli et al. (2013) showed that its afterglow properties are similar to those of very energetic, high-redshift GRBs, making it a genuine very high-L GRB.

Combining the findings on GRBs 120422A and 130427A lets us conclude that low- and high-L GRBs are not distinct populations of stellar explosions. They are due to the gravitational collapses of very massive stars and are accompanied by SNe. Their central engines are the same. Only the properties of their prompt emissions and of their afterglows (shock break-out vs. jet dominated) differ, depending on whether the jet can successfully drill through the stellar cocoon. This does not make them disjunct phenomena.

6. Summary and conclusions

We carried out extensive imaging and spectroscopy campaigns to study the intermediate luminosity GRB 120422A that shares properties of low-L and high-L GRBs. Our detailed analysis focussed on the GRB-SN 2012bz, the GRB afterglow, the host galaxy, and its environment.

We showed that SN 2012bz is the most luminous spectroscopically-confirmed GRB-SN to date, the peak luminosity being $M_{\rm V} = -19.7$ mag. The explosion physics parameters of $M_{\rm Ni} = 0.58$ M$_\odot$, $M_{\rm ej} = 5.87$ M$_\odot$, and $E_{\rm k} = 4.10 \times 10^{52}$ erg are among the largest values known to date. However, the exact values highly depend on the NIR contribution. Cano et al. (2011a) showed that the nickel and the ejecta masses and the kinetic energy can be underestimated by 25–45% if the NIR is not included in the modelling of the bolometric light curve. For future GRB-SN studies it is imperative to secure NIR data to place more stringent constraints on GRB progenitor models. As an alternative to a campaign with long wavelength coverage, the method presented in Lyman et al. (2013) would allow to construct the bolometric light curve from two optical light curves with well-determined k-corrections.

The spectral sequence of SN covers a time span of $\sim$ 40 days. All spectra are similar to that of other GRB-SNe. Differences exist in the strength of the absorption features and expansion velocities. For the first time, Fe IIλ5169 was used to trace the evolution of the GRB-SN expansion velocity. The velocities and their evolution are not very different from Si II measurements. Fe IIλ5169 has the advantage of being easier to identify and is detectable at earlier times We find an intriguing trend between the peak luminosity k and SN stretch factor s, similar to the Philips relation. Its significance is poor but several systematics affect the result.

GRB120422A was accompanied by one of the least luminous afterglows detected to date. Its blast-wave expanded with a low initial Lorentz factor of $\Gamma_0 \sim 60$ into a constant density medium and produced an very weak afterglow $L_{\nu,\,\rm max} \lesssim 2 \times 10^{30}$ erg s^{-1} Hz^{-1}. Thanks to the weak afterglow, we recovered emission from the cooling photosphere after the shock break-out, which was only observed for the low-L GRBs 060218 and 100316D. GRB 120422A's photosphere had a temperature of $\sim$ 16 eV and a radius of 7×10^13 cm at 1.4 hours after the GRB, typical values of SNe with detected shock break-out signatures. This fundamentally new quality for a non-low-L GRB questions whether 120422A is a genuine high-L GRB. Considering the properties of the prompt emission and the afterglow makes us conclude that GRB 120422A is the missing link between shock-break-out driven low-L and high-L GRBs that are powered by an ultra-relativistic jet, hence providing evidence for the failed-jet model for low-L GRBs.

The GRB occurred in an almost typical host galaxy. Its close to solar metallicity along with its negligible extinction makes it peculiar. Thanks to the large offset of 7.3 kpc from the nucleus, we perform spatially resolved spectroscopy. Surprisingly, even at the explosion site the metallicity is close to solar, while the SFR is not enhanced with respect to its immediate environment and only 1/10th of that of the galaxy's nucleus. Based on the N2 indicator we measure $Z = 0.8 \pm 0.1$ Z$_\odot$ at the explosion site. This does not necessarily mean that the GRB-hosting star-forming region had these properties. The X-shooter spectrum was only sensitive to a region of 4.0×3.9 kpc^2. What needs to be stressed is that emission-line measurements from low-resolution spectra should be taken with caution. Our medium resolution data revealed that the Hα line resolved in two components. This can lead in low-resolution data to an overestimation of the extinction and SFR.

Our narrowband imaging (width 15 Å) showed that the host is possibly interacting with a galaxy that lies at a projected distance of 23 kpc away. We identified two additional putative galaxy group members. In contrast to previous studies of GRB galaxy environments, tuneable filters allow us to more efficiently identify star-forming galaxies at a GRB's redshift. In particular, this approach is complementary to SED fitting techniques, which are limited to bright galaxies but not necessarily highly star-forming galaxies. Both approaches are needed to address the long-standing question on the peculiarity of GRB host galaxies and how galaxy interaction affects the production of GRB progenitors at low and high metallicities.

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Appendix A: Photometry of the optical transient

Table A.1. Log of optical and NIR observations

MJD (days)	Epoch (s)	Instrument	Filter	Exposure time (s)	Brightness ($\mathrm{mag_{AB}}$)
56039.308	664.2	*Swift*/UVOT	$uvw2$	38.9	> 20.27
56039.313	1110.2	*Swift*/UVOT	$uvw2$	38.9	$20.30^{+0.55}_{-0.36}$
56039.373	6244.8	*Swift*/UVOT	$uvw2$	332.2	$20.50^{+0.19}_{-0.16}$
56066.505	2350484	*Swift*/UVOT	$uvw2$	16823.3	> 24.05
56039.311	935.9	*Swift*/UVOT	$uvm2$	77.8	$20.84^{+0.75}_{-0.44}$
56039.370	5967.3	*Swift*/UVOT	$uvm2$	196.6	$20.89^{+0.47}_{-0.33}$
56039.436	11694.8	*Swift*/UVOT	$uvm2$	885.6	$21.03^{+0.23}_{-0.19}$
56066.471	2347530	*Swift*/UVOT	$uvm2$	16365	> 23.73
56039.311	912.7	*Swift*/UVOT	$uvw1$	58.3	> 20.56
56039.364	5454.6	*Swift*/UVOT	$uvw1$	393.2	$21.43^{+0.48}_{-0.33}$
56039.445	12479.4	*Swift*/UVOT	$uvw1$	645.3	$21.56^{+0.37}_{-0.28}$
56039.598	25671.6	*Swift*/UVOT	$uvw1$	1771.2	$21.47^{+0.21}_{-0.18}$
56067.110	2402743	*Swift*/UVOT	$uvw1$	11529.3	> 23.43
56039.305	387.2	*Swift*/UVOT	u	245.8	$21.06^{+0.51}_{-0.35}$
56039.311	898.9	*Swift*/UVOT	u	52.9	> 20.08
56039.366	5659.9	*Swift*/UVOT	u	393.2	$21.08^{+0.43}_{-0.31}$
56039.530	19853.4	*Swift*/UVOT	u	1770.3	$21.47^{+0.27}_{-0.21}$
56039.645	29800.8	*Swift*/UVOT	u	651.6	$21.41^{+0.39}_{-0.29}$
56042.104	242229.9	*Swift*/UVOT	u	11277.9	> 22.94
56051.997	1096947	*Swift*/UVOT	u	69897.4	$23.00^{+0.17}_{-0.14}$
56077.011	3258148	*Swift*/UVOT	u	27766.2	> 23.32
56039.339	3328.3	*Swift*/UVOT	b	451.6	> 20.42
56039.539	20641.6	*Swift*/UVOT	b	1523.7	$20.95^{+0.39}_{-0.28}$
56040.652	116790.9	*Swift*/UVOT	b	1444	> 21.07
56061.463	1914851	*Swift*/UVOT	b	7250.3	$21.54^{+0.36}_{-0.27}$
56093.296	4665241	*Swift*/UVOT	b	449.7	> 19.82
56039.302	90.4	*Swift*/UVOT	v	9	> 17.52
56039.311	912	*Swift*/UVOT	v	77.7	> 18.83
56039.541	20785.9	*Swift*/UVOT	v	1607.4	> 20.28
56041.111	156431	*Swift*/UVOT	v	1282.9	> 20.27
56093.300	4665526	*Swift*/UVOT	v	449.8	> 19.17
56039.990	59563	GROND	g'	4×115	22.21 ± 0.10
56040.015	61702	GROND	g'	4×369	22.12 ± 0.05
56040.036	63556	GROND	g'	4×369	22.15 ± 0.07
56040.040	63883	Gemini/GMOS	g'	1×60	22.22 ± 0.06
56040.057	65383	GROND	g'	4×369	22.11 ± 0.08
56040.089	68118	GROND	g'	8×369	22.18 ± 0.06
56040.173	75361	P60	g'	900	22.14 ± 0.10
56041.067	152661	GROND	g'	16×115	22.59 ± 0.10
56041.104	155811	GROND	g'	16×115	22.79 ± 0.16
56043.239	340286	Gemini/GMOS	g'	1×100	22.86 ± 0.06
56048.018	753173	GROND	g'	8×369	22.38 ± 0.10
56050.011	925358	GROND	g'	8×369	22.35 ± 0.08
56053.969	1267371	GTC/Osiris	g'	1×100	22.14 ± 0.11
56054.249	1291574	Gemini/GMOS	g'	1×30	22.16 ± 0.07
56059.005	1702443	GROND	g'	8×369	22.22 ± 0.04
56059.020	1703734	Gemini/GMOS	g'	1×120	22.19 ± 0.07
56067.938	2474262	GROND	g'	4×369	22.82 ± 0.05
56078.217	3362396	GROND	g'	24×115	23.29 ± 0.20

Notes. Magnitudes are corrected for Galactic extinction ($E(B-V) = 0.03\,\mathrm{mag}$). Column "Epoch" shows the logarithmic mean-time after the GRB in the observer frame. We only display the total observing time of the *Swift*/UVOT and P60 data (see Sect. 2.2 for details). As described in Sect. 2.3, photometry was tied to the SDSS DR8 standard ($'g'r'i'z'$) and to the 2MASS standard (JHK_s). For those filters not covered by our primary calibration systems ($RI_{\mathrm{C}}i_iY$) we used the instrument-specific band passes to transform magnitudes into the respective filter system.

MJD (days)	Epoch (s)	Instrument	Filter	Exposure time (s)	Brightness (mag_{AB})
56039.414	9793	Gemini/GMOS	r'	1×60	21.11 ± 0.04
56039.990	59563	GROND	r'	4×115	22.19 ± 0.14
56040.015	61702	GROND	r'	4×369	22.17 ± 0.07
56040.036	63556	GROND	r'	4×369	22.02 ± 0.05
56040.047	64459	Gemini/GMOS	r'	1×60	22.10 ± 0.05
56040.057	65383	GROND	r'	4×369	22.22 ± 0.07
56040.089	68118	GROND	r'	8×369	22.12 ± 0.08
56040.161	74357	P60	r'	900	22.28 ± 0.10
56040.888	137134	NOT/MOSCA	r'	4×300	22.28 ± 0.08
56041.068	152661	GROND	r'	16×115	22.34 ± 0.09
56041.104	155811	GROND	r'	16×115	22.47 ± 0.12
56041.949	228856	NOT/MOSCA	r'	12×300	22.23 ± 0.06
56042.938	314237	NOT/ALFOSC	r'	24×150	22.07 ± 0.06
56043.247	340990	Gemini/GMOS	r'	1×100	22.12 ± 0.06
56048.018	753173	GROND	r'	8×369	21.48 ± 0.05
56048.967	835203	NOT/StanCAM	R	8×150	21.45 ± 0.10
56050.011	925358	GROND	r'	8×369	21.33 ± 0.04
56052.958	1179975	Gemini/GMOS	r'	1×30	21.41 ± 0.10
56053.886	1260196	NOT/StanCAM	R	12×150	21.25 ± 0.06
56053.972	1267581	GTC/Osiris	r'	1×100	21.37 ± 0.14
56054.258	1292332	Gemini/GMOS	r'	1×30	21.26 ± 0.05
56056.895	1520199	NOT/ALFOSC	r'	8×150	21.23 ± 0.07
56059.032	1704797	Gemini/GMOS	r'	1×120	21.27 ± 0.05
56059.005	1702443	GROND	r'	8×369	21.21 ± 0.04
56061.962	1957915	Gemini/GMOS	r'	1×30	21.32 ± 0.06
56063.912	2126451	NOT/ALFOSC	r'	15×90	21.36 ± 0.08
56065.897	2297894	NOT/MOSCA	r'	16×90	21.48 ± 0.05
56065.968	2304100	Gemini/GMOS	r'	1×100	21.51 ± 0.04
56066.028	2309230	Magellan/LDSS3	r'	3×180	21.55 ± 0.04
56067.938	2474262	GROND	r'	4×369	21.65 ± 0.04
56067.957	2475887	NOT/MOSCA	r'	15×90	21.54 ± 0.08
56067.979	2477779	DuPont/CCD	r'	4×500	21.58 ± 0.05
56069.966	2649489	Gemini/GMOS	r'	1×100	21.73 ± 0.04
56069.902	2643961	NOT/MOSCA	r'	15×90	21.79 ± 0.07
56070.957	2735091	Gemini/GMOS	r'	1×100	21.77 ± 0.08
56071.907	2817199	NOT/ALFOSC	r'	10×90	21.96 ± 0.07
56078.217	3362396	GROND	r'	24×115	22.43 ± 0.11
56079.955	3512502	Gemini/GMOS	r'	1×30	22.41 ± 0.11
56083.915	3854715	NOT/ALFOSC	r'	20×90	22.39 ± 0.47
56039.322	1880	Gemini/GMOS	i'	1×240	20.93 ± 0.04
56039.896	51451	NOT/MOSCA	I	12×300	22.19 ± 0.08
56039.990	59563	GROND	i'	4×115	22.01 ± 0.18
56040.015	61702	GROND	i'	4×369	22.13 ± 0.07
56040.036	63556	GROND	i'	4×369	22.27 ± 0.10
56040.047	64459	Gemini/GMOS	i'	1×60	22.16 ± 0.06
56040.078	67209	GROND	i'	12×369	22.32 ± 0.09
56040.149	73289	P60	i'	900	22.23 ± 0.17
56040.871	135683	NOT/MOSCA	i'	4×300	22.48 ± 0.12
56041.067	152661	GROND	i'	16×115	22.50 ± 0.16
56041.104	155811	GROND	i'	16×115	22.59 ± 0.19
56041.924	226705	NOT/MOSCA	i'	6×300	22.37 ± 0.13
56042.866	308045	GTC/Osiris	i'	1×10	22.33 ± 0.14
56042.885	309735	NOT/ALFOSC	i'	13×300	22.35 ± 0.06
56043.255	341689	Gemini/GMOS	i'	1×100	22.29 ± 0.06
56043.874	395133	NOT/ALFOSC	i'	12×150	22.18 ± 0.08
56047.890	742159	NOT/ALFOSC	i'	3150[a]	21.56 ± 0.08
56048.018	753173	GROND	i'	8×369	21.56 ± 0.08
56048.987	836905	NOT/StanCam	i_i	8×150	21.52 ± 0.08
56050.011	925358	GROND	i'	8×369	21.49 ± 0.05
56053.916	1262736	NOT/StanCAM	i_i	12×150	21.34 ± 0.05
56053.903	1261613	GTC/Osiris	i'	1×100	21.20 ± 0.09
56063.974	1267805	GTC/Osiris	i'	1×100	21.27 ± 0.06
56054.163	1284132	P60	i'	1800	21.21 ± 0.14
56054.264	1292809	Gemini/GMOS	i'	1×30	21.29 ± 0.05
56055.175	1371560	P60	i'	3600	21.26 ± 0.11
56055.884	1432840	NOT/StanCAM	i_i	8×150	21.35 ± 0.05
56058.889	1692472	NOT/ALFOSC	i'	11×150	21.32 ± 0.07
56059.005	1702443	GROND	i'	8×369	21.27 ± 0.03
56059.005	1702494	Gemini/GMOS	i'	1×120	21.24 ± 0.04
56061.176	1890072	P60	i'	3240	21.22 ± 0.14
56062.181	1976858	P60	i'	3600	21.27 ± 0.15
56062.886	2037796	NOT/ALFOSC	i'	15×90	21.46 ± 0.22
56063.180	2063213	P60	i'	3600	21.33 ± 0.10
56063.891	2124602	NOT/ALFOSC	i'	10×120	21.41 ± 0.17
56065.921	2300003	NOT/MOSCA	i'	10×120	21.29 ± 0.05

(a) The image is a stack of images with different exposure times. The shown time is the sum of the single images.

Tab. A.1 — continued

MJD (days)	Epoch (s)	Instrument	Filter	Exposure time (s)	Brightness (mag_{AB})
56066.040	2310267	Magellan/LDSS3	i'	3×180	21.33 ± 0.04
56067.934	2473900	NOT/MOSCA	i'	10×120	21.35 ± 0.05
56067.938	2474262	GROND	i'	4×369	21.47 ± 0.06
56068.014	2480838	DuPont/CCD	i'	4×500	21.41 ± 0.04
56068.923	2559358	NOT/MOSCA	i'	19×60	21.39 ± 0.06
56069.1911	2582542	P60	i'	720	21.50 ± 0.09
56070.0313	2655131	Magellan/LDSS3	i'	3×300	21.40 ± 0.06
56070.1766	2667689	P60	i'	2340	21.59 ± 0.15
56070.9694	2736187	Gemini/GMOS	i'	1×120	21.62 ± 0.04
56071.8946	2816120	NOT/ALFOSC	i'	13×90	21.63 ± 0.08
56076.8994	3248536	NOT/ALFOSC	i'	20×90	21.98 ± 0.09
56078.2172	3362396	GROND	i'	24×115	22.06 ± 0.12
56079.8939	3507261	NOT/ALFOSC	i'	30×90	22.08 ± 0.11
56083.8841	3852020	NOT/ALFOSC	i'	20×90	22.15 ± 0.21
56039.9900	59563	GROND	z'	4×115	22.01 ± 0.20
56040.0360	63541	GROND	z'	12×369	22.09 ± 0.11
56040.0599	65605	Gemini/GMOS	z'	1×60	22.16 ± 0.11
56040.0890	68118	GROND	z'	8×369	22.37 ± 0.17
56041.0675	152661	GROND	z'	8×369	22.17 ± 0.16
56041.1039	155811	GROND	z'	8×369	22.28 ± 0.27
56043.2633	342383	Gemini/GMOS	z'	1×100	22.59 ± 0.07
56048.0179	753173	GROND	z'	8×369	21.86 ± 0.15
56049.8781	913895	CAHA/$Omega_{2000}$	z'	20×90	21.93 ± 0.08
56050.0107	925358	GROND	z'	8×369	21.78 ± 0.12
56052.2596	1119664	UKIRT/WFCAM	z'	4×360	21.44 ± 0.13
56053.9770	1268047	GTC/Osiris	z'	3×70	21.58 ± 0.07
56054.2708	1293429	Gemini/GMOS	z'	1×30	21.63 ± 0.06
56058.9733	1699722	Gemini/GMOS	z'	1×120	21.48 ± 0.04
56059.0048	1702443	GROND	z'	8×369	21.48 ± 0.07
56067.9101	2471861	NOT/MOSCA	z'	12×120	21.74 ± 0.15
56067.9379	2474262	GROND	z'	4×369	21.62 ± 0.07
56068.8970	2557129	NOT/MOSCA	z'	13×120	21.59 ± 0.12
56070.9776	2736894	Gemini/GMOS	z'	1×120	21.86 ± 0.06
56078.2172	3362396	GROND	z'	24×115	21.81 ± 0.12
56049.9204	917552	CAHA/$Omega_{2000}$	Y	20×90	21.93 ± 0.17
56039.3537	4589	UKIRT/WFCAM	J	360	20.20 ± 0.06
56039.3590	5048	UKIRT/WFCAM	J	360	20.33 ± 0.07
56039.3644	5514	UKIRT/WFCAM	J	360	20.36 ± 0.07
56039.3698	5979	UKIRT/WFCAM	J	360	20.41 ± 0.07
56048.9026	829616	CAHA/$Omega_{2000}$	J	60×60	21.60 ± 0.17
56049.9727	922069	CAHA/$Omega_{2000}$	J	30×60	21.83 ± 0.20
56052.2354	1117569	UKIRT/WFCAM	J	4×360	21.75 ± 0.24
56054.2834	1294514	Gemini-N/NIRI	J	1×60	21.96 ± 0.11
56065.2816	2244761	UKIRT/WFCAM	J	6×360	21.90 ± 0.15
56049.1898	854426	P200/WIRC	J	15×240	21.68 ± 0.16
56039.3757	6493	UKIRT/WFCAM	H	360	20.29 ± 0.09
56039.3812	6963	UKIRT/WFCAM	H	360	20.32 ± 0.09
56039.3866	7432	UKIRT/WFCAM	H	360	20.51 ± 0.11
56039.3919	7894	UKIRT/WFCAM	H	360	20.34 ± 0.10
56040.3685	92266	UKIRT/WFCAM	H	4×360	21.65 ± 0.42
56042.3348	262155	UKIRT/WFCAM	H	4×360	22.29 ± 0.31
56054.2376	1290555	Gemini-N/NIRI	K	1×60	21.46 ± 0.14

Tab. A.1 — continued

Appendix B: Late time observations

Table B.1. Summary of late-time observations

MJD (days)	Epoch (s)	Instrument	Filter	Exposure time (s)
56205.1849	14332405	CAHA/BUSCA	u'	13×45
56206.1974	14419882	CAHA/BUSCA	u'	50×45
56208.1930	14592304	CAHA/BUSCA	u'	21×45
56209.1754	14677188	CAHA/BUSCA	u'	52×45
56205.1849	14332405	CAHA/BUSCA	g'	13×45
56206.1974	14419882	CAHA/BUSCA	g'	50×45
56208.1930	14592304	CAHA/BUSCA	g'	21×45
56209.1754	14677188	CAHA/BUSCA	g'	52×45
56205.1849	14332405	CAHA/BUSCA	r'	13×45
56206.1974	14419882	CAHA/BUSCA	r'	50×45
56208.1930	14592304	CAHA/BUSCA	r'	21×45
56209.1754	14677188	CAHA/BUSCA	r'	52×45
56205.1849	14332405	CAHA/BUSCA	z'	13×45
56206.1974	14419882	CAHA/BUSCA	z'	50×45
56208.1930	14592304	CAHA/BUSCA	z'	21×45
56209.1754	14677188	CAHA/BUSCA	z'	52×45
56245.1818	17788140	LT/IO:O	r'	5×100
56254.1677	18564517	LT/IO:O	r'	9×100
56270.1558	19945888	LT/IO:O	r'	9×100
56275.1809	20380060	LT/IO:O	r'	9×100
56277.2116	20555512	LT/IO:O	r'	9×100
56279.0852	20717394	LT/IO:O	r'	9×100
56282.2041	20986865	LT/IO:O	r'	9×100
56283.0932	21063685	LT/IO:O	r'	9×100
56284.1360	21153781	LT/IO:O	r'	9×100
56296.0438	22182616	LT/IO:O	r'	9×100
56300.9702	22608259	LT/IO:O	r'	9×100
56302.1352	22708908	LT/IO:O	r'	9×100
56303.1084	22792994	LT/IO:O	r'	9×100
56303.9884	22869026	LT/IO:O	r'	9×100
56305.0037	22956752	LT/IO:O	r'	9×100
56306.0300	23045418	LT/IO:O	r'	9×100
56310.0862	23395876	LT/IO:O	r'	15×100
56310.9812	23473205	LT/IO:O	r'	15×100
56312.1042	23570230	LT/IO:O	r'	15×100
56360.9795	27793059	LT/IO:O	r'	15×100
56364.8835	28130364	LT/IO:O	r'	15×100
56365.9379	28221466	LT/IO:O	r'	15×100
56370.9299	28652774	LT/IO:O	r'	15×100
56309.4711	23342731	Gemini-N/GMOS	g'	5×100
56309.4704	23342671	Gemini-N/GMOS	r'	5×100
56309.4624	23341981	Gemini-N/GMOS	i'	5×100

Notes. Column "Epoch" shows the logarithmic mean-time after the burst in the observer frame.

Appendix C: X-shooter spectra of the afterglow and host galaxy's nucleus

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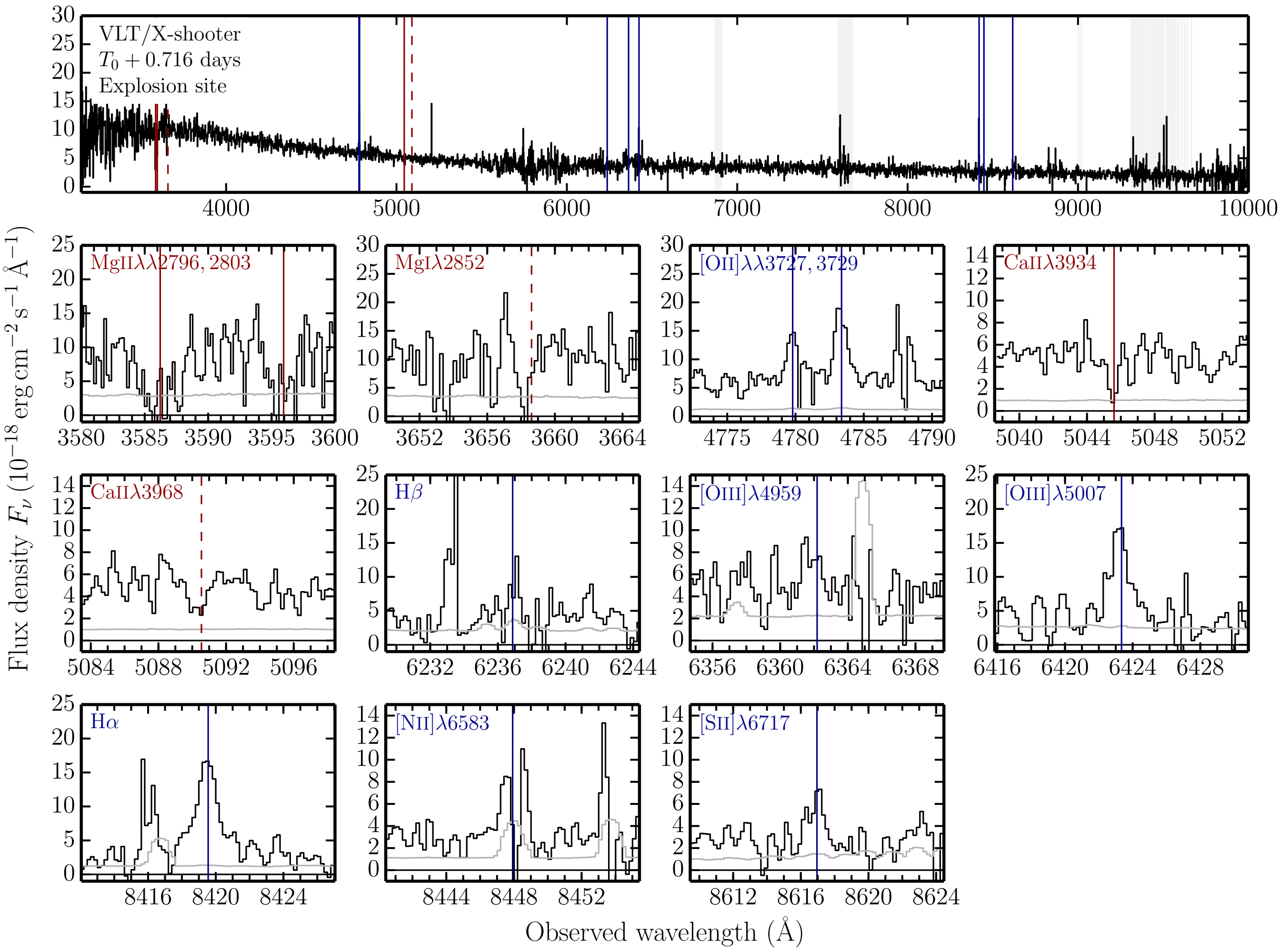

Fig. C.1. X-shooter spectrum of GRB 120422A's afterglow obtained 0.716 days after the burst. The top panel shows the combined UVB- and VIS-arm spectrum from 3150 to 10000 Å. The absolute flux-calibrated spectrum is corrected for heliocentric motion and Galactic reddening. The spectral data is shown in black, and the corresponding noise level in grey. For illustrative purposes we rebinned the spectrum to 2 Å bins. The positions of absorption lines that are typically associated with GRB absorbers are indicated by red lines (solid if detected and dashed if a feature evaded detection). Nebular lines are shown in blue. The panels below zoom in on each absorption and emission line (wavelength binning 0.15 Å) Table 4 summarises the fluxes and equivalent widths for each line. Regions that are heavily affected by atmospheric absorption (transparency: < 20%) are indicated by the grey shaded areas.

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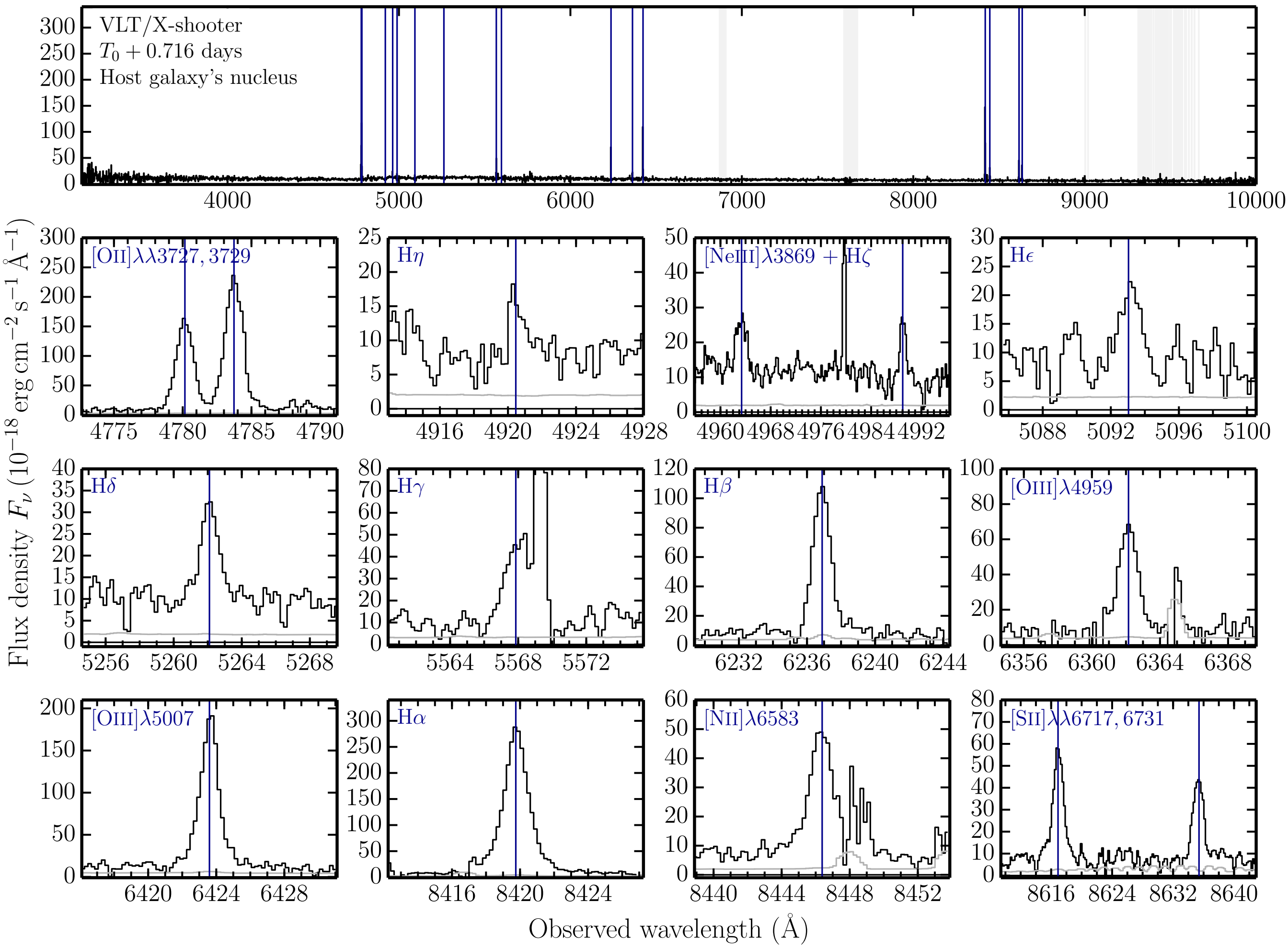

Fig. C.2. Same as Fig. C.1 but for the host galaxy's nucleus. Absorption lines are omitted since none was detected.