Multiwavelength analysis of three SNe associated with GRBs observed by GROND

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ABSTRACT

Context. After the discovery of the first connection between GRBs and SNe almost two decades ago, tens of SN-like rebrightenings have been discovered and about seven solid associations have been spectroscopically confirmed to date.

Aims. The luminosity and evolution origin of three SN rebrightenings in GRB afterglow light curves at z ∼ 0.5 are determined along with accurate determinations of the host-galaxy extinction. Physical parameters of the SN explosions are estimated, such as synthesised 56Ni mass, ejecta mass, and kinetic energy.

Methods. We employ GROND optical/NIR data and Swift X-ray/UV data to estimate the host-galaxy extinction by modelling the afterglow SED, to determine the SN luminosity and evolution, and to construct quasi-bolometric light curves. The latter were corrected for the contribution of the NIR bands using data available in the literature and blackbody fits. Arnett’s analytic approach has been employed to obtain the physical parameters of the explosion.

Results. The SNe 2008hw, 2009nz, and 2010ma observed by GROND exhibit 0.80, 1.15, and 1.78 times the optical (r‘ band) luminosity of SN 1998bw, respectively. While SN 2009nz exhibits an evolution similar to SN 1998bw, SNe 2008hw and 2010ma show earlier peak times. The quasi-bolometric light curves (340 – 2200 nm) confirm the large luminosity of SN 2010ma (1.4 × 1051 erg s−1), while SNe 2008hw and 2009nz reached a peak luminosity closer to SN 1998bw. The modelling resulted in 56Ni masses of around 0.4 – 0.5 M⊙.

Conclusions. By means of the a very comprehensive data set, we found that the luminosity and the 56Ni mass of SNe 2008hw, 2009nz, and 2010ma resembles those of other known GRB-associated SNe. This findings strengthens previous claims of GRB-SNe being brighter than type-Ic SNe unaccompanied by GRBs.

Key words. gamma-ray burst: individual: GRB 081007 – supernovae: individual: SN 2008hw – gamma-ray burst: individual: GRB 091127 – supernovae: individual: SN 2009nz – gamma-ray burst: individual: GRB 101219B – supernovae: individual: SN 2010ma

1 Introduction

Gamma-ray bursts (GRBs) and supernovae (SNe) correspond to the most energetic explosions in the Universe with a radiative energy release of about 1051–53 erg. Nowadays the observational evidence points towards the catastrophic deaths of massive stars, which are thought to give birth to both long GRBs ( durations ≳ 2 s; Kouveliotou et al. 1993) and broad-lined (BL) type-Ic SNe after the collapse of their cores into a black hole ( BH; Paczyński 1986; Fryer et al. 1999; van Paradijs et al. 2000). Known as the collapsar model ( Woosley 1993; MacFadyen & Woosley 1999, Bromberg et al. 2012), the collapsing core of a very massive star can lead to the formation of a relativistic jet that will produce high-energy emission ( Woosley 1993; Woosley & MacFadyen 1999) in the form of a GRB or an X-ray flash ( XRF; Heise et al. 2001; Kippen et al. 2004; Sakamoto et al. 2008). The γ-ray emission itself lasts from a few tenths of a second to a few thousand seconds, is generated within the outflow at ultra-relativistic velocities, and is collimated into a jet (Zhang & Mészáros 2009) that drills its way out of the star. The interactions between fireball shells with different speeds (“internal shocks”) are responsible for the prompt γ-ray emission. The multi-wavelength afterglow (AG), detectable from radio throughout to X-rays up to months after the GRB ( e.g., Kann et al. 2010, 2011), is explained by the synchrotron emission produced in the interaction between the circumburst material and the relativistic outflow (“external shocks”; see Zhang & Mészáros 2004 for a review).

In principle, the energy transferred to the envelope should also be capable of causing the ejection of the stellar envelope (Burrows 2000; Heger et al. 2003). However, it is unclear how or even if there is always enough energy for the SN explosion (“fall-back” events, e.g., Fryer et al. 2007a, and references therein).
of GRB-SNe (including bumps not spectroscopically identified) have analysed the luminosity distribution, the light-curve morphology, and the explosion physical parameters such as kinetic energy \(E_k\), ejected mass \(M_{ej}\), and \(^{56}\)Ni mass \(M_{Ni}\) (Richardson 2009; Thöne et al. 2011; Cano 2013). They concluded that GRB-SNe are in general brighter than the local sample of SE SNe, except for cases of exceptionally bright type-Ic SNe (e.g., SN 2010ay, Sanders et al. 2012; SN 2010gx, Pastorello et al. 2010). Regarding light-curve morphology, Stanek et al. (2005) and more recently Schulze et al. (2014) claim to have found a correlation between brightness and light-curve shape, which was also confirmed by Cano (2014) using a larger sample and including the appropriate K corrections. This strengthens the use of GRB-SNe as standard candles for cosmology (see also recent studies by Li & Horiuti 2014; Cano & Jakobsson 2014 and Li et al. 2014). While more than two dozen photometric bumps in AG light curves have been presented as SE rebrightenings (e.g., Richardson 2009), so far only seven have been confirmed through high-SN spectra: SNe 1998bw, 2003dh, 2003lw, 2006aj, 2010bh, 2012bz, 2013dx, and 2013cq.

The energy injection of a newly-formed rapidly-spinning strongly-magnetised NS (so-called “magnetar”) provides an alternative scenario for GRB-SNe. Here the SN is powered by the dipole-field strength of the magnetar (e.g., Woosley 2005; Dessart et al. 2012). Magnetars have been linked to the GRB emission too, because their outflows can explain the energetics of long-duration GRBs (e.g., Bucciantini et al. 2009; Metzger et al. 2011). Moreover, the \(E_k\) of GRB-SNe (\(\sim 10^{52}\) erg) is fairly consistent with the maximum rotational energy of a NS with a period of 1 ms (Mazzali et al. 2006). GRB-SN zoo is claimed to be entirely produced by magnetars and driven by the SN rather than by the GRB jet (Mazzali et al. 2014).

Three detected SNe associated with GRB counterparts are the main focus of this paper: SNe 2008bw (GRB 081007), 2009hnz (GRB 091127), and 2010ma (GRB 101219B). The acquisition, reduction, and calibration of the multiwavelength data are described in Sect. 2. The corresponding analysis is presented in Sect. 3 along with further discussion in Sect. 4. Finally, we summarise our conclusions in Sect. 5.

2. Data

For the three objects of interest, the data was obtained by the X-Ray Telescope (XRT; Burrows et al. 2005) and the Ultra-Violet Optical Telescope (UVOT; Roming et al. 2005) both on board the Swift satellite (Gehrels et al. 2004) and by the Gamma-Ray burst Optical and Near-infrared Detector (GROND; Greiner et al. 2007, 2008), the seven-channel imager mounted on the MPG 2.2-m telescope at La Silla, Chile. The whole data set comprises X-ray photometry and spectra from 0.2 – 10 keV, UV/optical photometry in the \(uvw2, uvm2, uvw1, b, v, u\) filters, and optical/NIR photometry in the \(g', r', i', z', J, H, K_s\) bands, spanning four orders of magnitude in the energy spectrum.

The UVOT/XRT data retrieval and the GROND/UVOT methodology towards the final photometry are detailed in Olivares E. et al. (2012). Optical image subtraction of the host galaxy was performed for GRB 081007/SN 2008bw and GRB 091127/SN 2009hnz. All data presented are corrected for the Galactic foreground reddening \(E(B-V)_{\text{Gal}}\) in the direction of the burst (Schlegel et al. 1998). The reddening is transformed to the extinction \(A_{\text{V,Gal}}\) by assuming a ratio of total to selective absorption of \(R_{V,Gal} = 3.1\) from the Milky-Way (MW) reddening law. The final GROND photometry is presented in Appendix A. All magnitudes throughout the paper are in the AB system.
Table 1. GROND sample of GRB-associated SNe.

| GRB        | SN       | RA(J2000) [°, ' ,"] | Dec.(J2000) [°, ' ,"] | z     | d^2 [Mpc] | A^2_{Gal} [mag] | N^2_{H,Gal} [10^{20} cm^{-2}] | Refs. |
|------------|----------|----------------------|------------------------|-------|-----------|----------------|-----------------------------|-------|
| 081007     | 2008hw   | 22:39:50.40          | −40:08:48.8            | 0.530 | 2885      | 0.05           | 1.4                         |       |
| 091127     | 2009nz   | 02:26:19.87          | −18:57:08.6            | 0.490 | 2628      | 0.12           | 2.8                         |       |
| 101219B    | 2010ma   | 00:48:55.35          | −34:33:59.3            | 0.552 | 3022      | 0.06           | 3.1                         |       |

Notes.  
(1) The luminosity distances are computed using the ΛCDM cosmological model (Ω_{M} = 0.27, Ω_{Λ} = 0.73, and H_0 = 74.2 km s^{-1} Mpc^{-1}; Riess et al. 2009) and the redshifts corrected by the local velocity field (Mould et al. 2000).  
(2) The Galactic foreground extinction values are taken from the dust maps of Schlegel et al. (1998).  
(3) The absorption column densities are taken from the Galactic H I maps of Kalberla et al. (2005).

References. Redshifts are taken from (1) Berger et al. 2008, (2) Vergani et al. 2011, (3) Sparre et al. 2011.

Table 2. GROND photometry of the host galaxies.

| GRB        | SN       | g' r' i' | z' | J | H | K_s |
|------------|----------|---------|----|---|---|-----|
| 081007     | 2008hw   | 24.66 ± 0.11 | 24.94 ± 0.11 | 24.08 ± 0.19 | 23.96 ± 0.24 | > 22.0 | > 21.1 | > 20.1 |
| 091127     | 2009nz   | 24.08 ± 0.09 | 23.45 ± 0.06 | 22.85 ± 0.07 | 22.95 ± 0.08 | > 21.7 | > 21.4 | > 19.9 |
| 101219B    | 2010ma   | > 25.4  | > 25.2 | > 24.5 | > 24.5 | > 22.2 | > 22.0 | > 20.2 |

Notes. The host-galaxy magnitudes are all corrected for the corresponding Galactic foreground extinction. The upper limits were derived from the deepest observation available showing no detection and are quoted at the 3σ confidence level.

3. Three GRB-associated SNe detected by GROND

Table 1 presents a sub-sample of GRBs with late-time optical SN rebrightenings in their AG light curves, all of them observed by GROND. Deep late-time observations were carried out for each of them to constrain the contribution from their host galaxies. If the host was detected, we performed image subtraction. Table 2 presents the resulting photometry for those host galaxies. In the following, observational facts and general properties of each event are summarised from the literature. If possible, mass estimates are derived from the SEDs of the host galaxies using the hyperZ code (Bolzonella et al. 2000) and a library of galaxy spectral templates extinguished by the different reddening laws.

GRB 081007/SN 2008hw  
The Swift/BAT (Barthelmy et al. 2005) discovered GRB 081007 at 05:23:52 UT on 2008 October 7 (Baumgartner et al. 2008). The prompt emission had a duration of T_{90} ≈ 10 s and a soft spectrum with E_{peak} ≤ 30 keV (Markwardt et al. 2008). The redshift of z = 0.5295 was found by Berger et al. 2008 through optical spectroscopy. A subsequent optical spectrum taken 17 days after the burst shows broad features indicative of an emerging SN, which was thereafter classified as type I (no Hydrogen lines) and named SN 2008hw (Della Valle et al. 2008). The SN bump was also reported as a flux excess with respect to the AG (Soderberg et al. 2008). The GROND photometry of the host galaxy (Table 2) from August 31, September 30, and October 21, 2011, yields a stellar-mass range of $M_\ast \approx 10^{5} – 9 \ M_\odot$, which is compatible with the population of GRB hosts (Savaglio et al. 2009). Using appropriate transformation equations 2 our host magnitudes are somewhat brighter but marginally consistent with the measurements published by Jin et al. (2013) of R_C > 24.67 and I_C = 24.29 ± 0.20 mag at ~ 87 d after the GRB.

GRB 091127/SN 2009nz  
At 23:25:45 UT on 2009 November 27, the Swift/BAT was triggered by GRB 091127 (Troja et al. 2009). The γ-ray emission lasted for T_{90} = 7.1 s and showed a soft spectrum (Stamatikos et al. 2009; Troja et al. 2012). A redshift of z = 0.490 was obtained from optical spectroscopy (Cucchiara et al. 2009; Thöne et al. 2009). Observations by Konus-Wind confirmed the results from the Swift/BAT (Golenetskii et al. 2009) and additionally yielded an energy release typical for cosmological GRBs (E_{iso} ∼ 10^{52} erg). The optical AG was confirmed with GROND observations (Updike et al. 2009) adding NIR detections. The full analysis of the GROND AG light curve was presented in Filgas et al. (2011). The SN classification became official based on the photometric SN bump (Cobb et al. 2010b) and spectroscopy was published later showing BL features (Berger et al. 2011). Photometry depicting the SN rebrightening was published in Cobb et al. (2010c) and Vergani et al. (2011). Using the host-galaxy detections in GROND optical imaging (October 31, 2010) and in NIR photometry from Vergani et al. (2011), a stellar mass of $M_\ast = 10^{5} – 9 \ M_\odot$ is obtained. This value falls in the low-mass end of the observed distribution of GRB host masses (Savaglio et al. 2009) and is compatible with the stellar mass computed by Vergani et al. (2011).

GRB 101219B/SN 2010ma  
At 16:27:53 UT on 2010 December 19, the Swift/BAT discovered GRB 101219B (Gelbord et al. 2010). The BAT burst lasted T_{90} = 34 s (Cummings et al. 2010) and consisted of a spectrum with E_{peak} ∼ 70 keV as observed by Fermi/GBM (van der Horst 2010). The SN discovery was first reported photometrically by Olivares E. et al. (2011) along with a redshift estimation assuming the brightness of SN 1998bw for the rebrightening ($z = 0.4 – 0.7$). The spectroscopic confirmation of SN 2010ma came later by Sparre et al. (2011) along with the redshift determination of $z = 0.55185$ from weak Mg absorption lines. The spectroscopy lead to further analysis by Sparre et al. (2011b) that shows broad-line features characteristic of GRB-SNe. Late-time GROND observations on September 30, 2011, show no signal of a host-galaxy down to deep limits (Table 2), therefore no image-subtraction procedure was performed. These upper limits imply a stellar mass for the host galaxy of $M_\ast \lesssim 10^{2} – 5 \ M_\odot$, which corresponds to the low-mass half of observed GRB host mass distribution and is marginally compatible with the Small Magellanic Cloud (SMC).
3.1. Multicolour light-curve fitting

After image subtraction of the host galaxy in the cases where it was detected (Table 3), the light curves were fitted simultaneously using one or two power-law components \( F_\nu \sim t^{\alpha} \) and templates of SN 1998bw, where corrections due to redshift and Galactic foreground extinction were taken into account (see Zeh et al. 2004, for details on the fitting of SN 1998bw templates). Simultaneous modelling consists of unique power-law slopes \( \alpha_1, \alpha_2 \) and SN-template stretch factor \( s \) for all bands. The ratio between the luminosity of the observed SN and that of SN 1998bw (luminosity ratio \( \kappa \); Zeh et al. 2004) represents the free brightness parameter, which was fitted to the light curves corrected for Galactic extinction only. Therefore, the luminosity ratios are then corrected for the host-galaxy extinction \( A_{\lambda,\text{host}} \) determined by the SED modelling (see Sect. 3.2). The modelling is described in detail below for each event and summarised in Tables 3 and 4.

**GRB 081007/SN 2008hw**  Figure 1 shows that the light curves in all seven bands are well modelled using a broken power law (Beuermann et al. 1999). The \( g' r' i' z' \) photometry has been image-subtracted to remove the host-galaxy flux. The X-ray light curve from the Swift/XRT was included in the fitting to constrain the decay after the break, where there is only a single optical epoch. For the \( r' i' z' \) bands, it was necessary to add a supernova component with a luminosity about 65–80% that of SN 1998bw (see Table 4). Due to the \( JHK_s \) flux excesses with respect to the broken power law at roughly 1 day after the burst, a constant component was included in the modelling for these bands. The \( g' \) band upper limit is strongly affected by absorption of metal lines and wavelength extrapolation of the SN 1998bw template (e.g., the case of SN 2009nz due to high redshift). Jin et al. (2013) report a luminosity 50% that of SN 1998bw template (e.g., the case of SN 2009nz due to high redshift). Jin et al. 2013 report a luminosity 50% that of SN 2009nz template and the UV line blanketing by metals. Even though the host galaxy remained undetected, it may explain the flux excesses by absorption-line blanketing of metals, and 3.2. The modelling is described in detail below for each event and summarised in Tables 3 and 4.

**GRB 091127/SN 2009nz** Figure 2 presents the light curves of the AG in six bands. The \( g' r' i' z' \) photometry has been image-subtracted to remove the host-galaxy flux. All are well fitted by a single power law, which needed a SN component for the \( g' r' i' z' \) bands. No \( K_s \)-band observations were obtained for this event (Filgas et al. 2011). The brightest host galaxy allowed by the data was included in the model for JH at late times (see Table 2). The \( k \) and \( s \) values reflect strong similarities to SN 1998bw in the \( r' i' z' \) bands. At the redshift of SN 2009nz (z = 0.490), the \( g' \) band is probing wavelengths centred at \( \lambda \sim 3000 \) Å, where the flux is strongly affected by absorption-line blanketing of metals, and so the intensity can differ from SN to SN. Moreover, since the U band, the bluest band from which the SN 1998bw templates are constructed, is sensitive \( \lambda \sim 3000 \) Å, extrapolations dominate the \( g' \)-band template. Given also the non-detections after day 12, we derived an upper limit of \( k_{g'} < 1.21 \) from the fitting (Table 4).

**GRB 101219B/SN 2010ma** Figure 3 shows the GROND light curves of the optical counterpart. The SN bump is clearly seen in the \( r' i' z' \) bands, however, it is less significant in the \( g' \) band. At the redshift of the event, the \( g' \) band actually probes the UV regime, therefore, the lower \( g' \)-band SN luminosity is explained by a combination of both the wavelength extrapolation of the template and the UV line blanketing by metals. Even though the host galaxy remained undetected, it may explain the flux excesses by absorption-line blanketing of metals, and 3.2. The modelling is described in detail below for each event and summarised in Tables 3 and 4.

![Fig. 1. Multicolour light curves of GRB 081007/SN 2008hw corrected for Galactic extinction as observed by the Swift/XRT (upper panel) and GROND (lower panel). Filled circles represent detections and arrows are upper limits. Solid lines correspond to the overall fits and dotted lines to the AG component. For clarity, light curves were shifted along the magnitude axis. Shallow upper limits are not shown (see Table A.1 for the complete data set).

![Fig. 2. Multicolour GROND light curves of GRB 091127/SN 2009nz corrected for Galactic extinction. Only data after day one has been employed. The symbol and line coding is the same as Fig. 1 as well as the vertical shift for clarity.](image-url)
Table 3. Parameters of the AG component and goodness of the light-curve modelling.

| GRB    | $\alpha_1$ | $t_{\text{break}}$ [days] | $\eta$ | $\alpha_2$ | $\chi^2/\mu$ |
|--------|------------|---------------------------|--------|------------|--------------|
| 081007 | $-0.66 \pm 0.01$ | $0.91 \pm 0.05$ | 15 fixed | $-1.40 \pm 0.05$ | 1.5          |
| 091127 | $-0.38 \pm 0.01^a$ | $0.34 \pm 0.01^a$ | $1.3 \pm 0.1^a$ | $-1.63 \pm 0.02$ | 1.4          |
| 101219B | $-1.01 \pm 0.01$ | $\cdots$ | $\cdots$ | $\cdots$ | 1.8          |

Notes. The primary power-law slope is $\alpha_1$. In case of a break in the light curve, a secondary slope $\alpha_2$ along with the break time $t_{\text{break}}$ and break smoothness parameter $\eta$ are introduced. The ratio $\chi^2/\mu$ is computed in the multiple-component fitting procedure, which includes AG plus SN modelling. See Table 4 for the SN parameters. (a) Parameters were taken from the fitting of the full GROND $r'$-band light curve by Figas et al. (2011) except $\alpha_2$, which was fitted by a single power law using the data presented in Fig 3 only.

Table 4. Parameters of the SN component with respect to SN 1998bw templates.

| SN       | GRB    | Stretch factor (s) | $g'$ | $r'$ | $i'$ | $z'$ |
|----------|--------|--------------------|------|------|------|------|
| 2008hw   | 081007 | $0.85 \pm 0.11$   | < 0.90 | 0.80 $\pm$ 0.10 | 0.65 $\pm$ 0.08 | 0.69 $\pm$ 0.10 |
| 2009nz   | 091127 | $1.03 \pm 0.04$   | < 1.21 | 1.15 $\pm$ 0.09 | 0.96 $\pm$ 0.14 | 0.73 $\pm$ 0.12 |
| 2010ma$^b$ | 101219B | $0.76 \pm 0.10$ | 0.85 $\pm$ 0.17 | 1.78 $^{+0.08}_{-0.17}$ | 1.36 $\pm$ 0.09 | 0.63 $\pm$ 0.09 |

Notes. ($^a$) Luminosity ratios are all corrected for Galactic and host-galaxy extinction. The latter correction is taken from the AG SED fitting in Sect. 3.2. ($^b$) No host-galaxy contribution was assumed. See text for estimations including host emission.

3.2. Spectral energy distributions

Using the available X-ray data from the Swift/XRT, the UV/optical data from the Swift/UVOT, and the optical/NIR data from GROND, we constructed a single AG SED per event with the main purpose of determining the extinction along the line of sight through the host galaxy. The SED modelling was performed similarly as in Greiner et al. (2011) and the results are presented in Table 5.

![Fig. 3. Multicolour GROND light curves of GRB 101219B/SN 2010ma corrected for Galactic extinction. The symbol and line coding is the same as in Fig. 1 as well as the vertical shift for clarity. The red dashed line represents a model with an extra host-galaxy component.](image)

![Fig. 4. Colour curves corrected for the total extinction of SNe 2008hw (blue circles), 2009nz (purple squares), and 2010ma (gold diamonds) after AG and host subtraction. Blue, purple, and gold solid lines are computed from the templates of SN 1998bw at the redshifts of SNe 2008hw, 2009nz, and 2010ma, respectively.](image)
Table 5. Parameters of the SED modelling of the AG.

| GRB       | $\beta_X$         | $A_{V,\text{host}}$ [mag] | $E_{\text{break}}$ [eV] | $N_{\text{H,host}}$ [$10^{21}$ cm$^{-2}$] | $\chi^2/\mu$ |
|-----------|-------------------|-----------------------------|--------------------------|---------------------------------|-------------|
| 081007    | 0.97 ± 0.09       | 0.68 ± 0.08 (SMC)           | 37 ± 54                  | 5.6 ± 0.7                       | 1.1         |
| 091127$^a$| 0.748 ± 0.004     | < 0.03 (LMC)                | 2.6 – 29.9               | 0.32 ± 0.06                     | 1.1         |
| 101219B   | 1.12 ± 0.01       | 0.12 ± 0.01 (SMC)           | 9.0 fixed                | 0.6 ± 0.3                       | 0.8         |

Notes. Obeying the fireball model for GRB AGs, the high-energy ($\beta_X$) and the low-energy ($\beta_{\text{opt}}$) spectral indexes are correlated by $\beta_X = \beta_{\text{opt}} + 0.5$ for $E_{\text{break}} \approx E_{cooling}$. Where the latter comes from the cooling frequency of the electrons, except in the case of GRB 091127 where $\beta_{\text{opt}}$ varies in the range 0.25 – 0.62. $^a$The quoted values of $\beta_X$, $N_{\text{H,host}}$, and reduced $\chi^2$ are computed from the simultaneous best fit to all eight GROND/XRT SEDs by Filgas et al. (2011). The $E_{\text{break}}$ range comes from an observed evolution of $\beta_{\text{opt}}$. The $A_{V,\text{host}}$ upper limit was taken from Schady et al. (2012).

Note that the AG may probe a slightly different line of sight than the SN photosphere. If anything, the extinction for the SN should be larger than for the AG, because the AG forms further out, where the material ejected by the GRB hits the circumstellar medium. In the standard fireball shock model, this radius is about $10^{17}$ cm (and even larger for low-luminosity events; Molinari et al. 2007). Moreover, dust can be formed in the SN ejecta, although not significant amounts on such short timescales (e.g., Smith et al. 2012). Therefore, we considered that the extinction determined through the AG SED is valid for the SN component as well. The following corresponds to a description of the SED fitting for each of the rebrightenings.

**GRB 081007/SN 2008hw** To include contemporaneous Swift/UVOT data, the second GROND epoch was chosen to study the broad-band SED of GRB 081007 presented in Fig. 5. From the UVOT, upper limits in the UV bands are included, which help to constrain the host-galaxy extinction. The time-integrated Swift/XRT spectrum was interpolated to the epoch of the UV/optical observations. The resulting values of host-galaxy extinction and their corresponding statistical uncertainty are consistent with those computed by Covino et al. (2013) and for the GROND filters we obtain $A_{V,\text{host}} = 1.39 ± 0.16$, $A_{r,\text{host}} = 0.99 ± 0.12$, $A_{\lambda,\text{host}} = 0.77 ± 0.09$, $A_{J,\text{host}} = 0.63 ± 0.07$, $A_{K,\text{host}} = 0.38 ± 0.04$, $A_{H,\text{host}} = 0.24 ± 0.03$, and $A_{\text{K,host}} = 0.14 ± 0.02$ in the observer’s frame, all in units of magnitude. These values were used to correct the SN luminosity ratios shown in Table 5.

**GRB 091127/SN 2009nz** The broad-band SEDs of the early AG of GRB 091127 were presented by Filgas et al. (2011) using the GROND data. A detailed analysis by Schady et al. (2012) includes Swift/UVOT and GROND data and constrains the host-galaxy extinction, which results in $A_{V,\text{host}} < 0.03$ mag. The SED parameters are shown in Table 5.

**GRB 101219B/SN 2010ma** Using GROND, XRT, and UVOT data combined, the AG SED of GRB 101219B was constructed at 9 h after the burst. Figure 6 shows a broken power law as the best fit. The values of the required host-galaxy extinction for the GROND filters and their corresponding statistical uncertainty in the observer’s frame are $A_{V,\text{host}} = 0.25 ± 0.03$, $A_{r,\text{host}} = 0.18 ± 0.02$, $A_{\lambda,\text{host}} = 0.14 ± 0.02$, $A_{J,\text{host}} = 0.11 ± 0.01$, $A_{K,\text{host}} = 0.07 ± 0.01$, $A_{H,\text{host}} = 0.04 ± 0.01$, and $A_{\text{K,host}} = 0.026 ± 0.003$, all in units of magnitude.

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Fig. 5. Broad-band AG SED of GRB 081007 at 1.6 ks after trigger. The arrows are 3σ upper limits. The best-fit model (thick line) is an extinguished broken power law. The thin line represents the unextinguished model. The residuals are in units of $\chi$ (lower panel).

Fig. 6. Broad-band AG SED of GRB 101219B at 9.0 h after trigger. The symbols, the line coding, and the panels are the same as in Fig. 5.
3.3. Calculation and modelling of the bolometric light curves

To isolate the SN from the AG evolution, the light-curve models computed in Sect. 3.3.1 were employed. The AG contribution was calculated from the model for the epochs when the SN bump was observed and it was subtracted from the light curves for each filter. The uncertainties in the model were appropriately propagated to the final magnitude errors. After the AG subtraction, quasi-bolometric light curves were computed for each of the three events by numerically integrating the monochromatic fluxes in the wavelength range from 340 to 700 nm. The redshift-based luminosity distances in Table 1 were employed to transform observed into absolute flux. The total uncertainty in the luminosity distance is about 10% and has not been included in the quasi-bolometric light curves.

3.3.1. NIR bolometric correction

The NIR luminosity proves critical when estimating the bolometric flux and consequently the physical parameters of the explosion obtained via the quasi-bolometric flux. However, SNe 2008bw, 2009nz, and 2010ma remained undetected in the $JHK$ bands. To account for the NIR flux of these SNe, we proceeded with two different methods. First of all, we defined the NIR flux from 700 to 2200 nm in the rest frame and the quasi-bolometric flux from 340 to 2200 nm. The quantity to be estimated via the two methods is the ratio between the NIR flux and the quasi-bolometric flux as defined above.

The first method consisted in estimating the NIR fraction of the quasi-bolometric flux using the observed NIR data available in the literature. With the optical/NIR photometry, we computed the ratio between the NIR and the quasi-bolometric fluxes for the GRB-SNe 1998bw (Kocevski et al. 2007) and 2006aj (Patat et al. 2001), and for the type-Ib/c SNe 2002ap (Foley et al. 2003; Yoshii et al. 2003), 2007uy (Roy et al. 2013), and 2008D (Modjaz et al. 2009). We show the observed NIR fractions in the upper panel of Fig. 7 along with a quadratic-polynomial fit for each SN. For each fit, we also obtained the corresponding uncertainty as a function of time. By taking the weighted average per time bin (5-days width, $t_i = 1$ d), we derived the joint evolution of the NIR fraction for the five SNe. The non-weighted RMS was taken as the $1\sigma$ error. Only the first time bin uses data from a single event and the error here is approximated by the uncertainty in the individual polynomial fit. The binned NIR fraction was interpolated using quadratic polynomials to retrieve values for a given time and to plot the grey contours in Fig. 7. The SNe 2007uy and 2008D do not contribute much to the weighted average, because their host extinction is large and highly uncertain (0.3 – 0.5 mag; Mazzali et al. 2008; Roy et al. 2013).

The second method assumes that the SN atmosphere at early phases resembles a cooling black body (BB; e.g., Arnett 1982; Filippenko 1997; Dessart & Hillier 2005). We defined a simple BB model with the temperature and a flux normalisation as free parameters. Then, we modelled the SN SEDs constructed using $g'r'i'z'$ data at each epoch. The results of the fitting procedure are shown in Appendix C. We obtain colour temperatures decreasing with time and consistent with other SE SNe (e.g., Folatelli et al. 2014). The extrapolation into the NIR range delivered NIR fractions plotted in the lower panel of Fig. 7 with uncertainties between 0.05 and 0.13. The increasing NIR flux with time is consistent with the scenario of the cooling envelope. We repeated this procedure for the optical data of SNe 1998bw ($UBVRI$: Galama et al. 1998) and 2006aj ($UBVRI$: Pian et al. 2006; Sollerman et al. 2006) with results that are consistent with those for SNe 2008bw, 2009nz, and 2010ma. Moreover, the $1\sigma$ contours (grey-shaded region) are compatible with the all BB estimates derived using optical photometry solely.

The final NIR correction applied to the optical data was the average value between the estimates from the available NIR data for GRB-SNe and the estimates from the BB fits. A conservative proxy of the NIR-fraction error was chosen to be the largest among the difference between the two estimates and their respective errors. Errors fluctuate between 0.07 and 0.22. We note that the NIR correction implies $JHK$ magnitudes at maximum consistent with the upper limits presented in Figs. 1, 2, and 3. For instance, the brightest magnitudes derived from the NIR correction are $J \approx 22.6$, $H = 23.2$, and $K_s = 23.6$ mag for SN 2010ma. The corrected measurements of the quasi-bolometric flux are presented in Fig. 8 for the GRB-SNe 2008bw, 2009nz, and 2010ma. For comparison, the quasi-bolometric light curves (340 – 2200 nm) for other SE SNe are also computed and plotted in Fig. 8. We note that all three events lie at luminosity comparable to that of GRB-SNe 1998bw and 2006aj and are brighter than “normal” type-Ib/c SNe. Similar to the results we obtain for individual optical filters, SN 2010ma turns out to be brighter than SN 1998bw. The quasi-bolometric fluxes of SNe 2008bw, 2009nz, and 2010ma at maximum (Table 6) are comparable to $(1.07 \pm 0.07) \times 10^{53}$ erg s$^{-1}$ for SN 1998bw.
The nickel mass $M_{\text{Ni}}$, the ejected mass $M_{\text{ej}}$, and the kinetic energy $E_k$ of the explosion were extracted from the luminosity models following the analytic approach by Arnett (1982) for $^{56}$Ni-powered SNe (see, e.g., Maeda et al. 2003, Taubenberger et al. 2008, Valenti et al. 2008, Pignata et al. 2011, Olivares E. et al. 2012, Roy et al. 2013). We therefore employed the following expression to model the bolometric luminosity:

$$L(t) = M_{\text{Ni}} e^{-\tau_m} \left[ (\epsilon_{\text{Ni}} - \epsilon_{\text{Co}}) \int_0^s A(z) \, dz + \epsilon_{\text{Co}} \int_0^{\tau_m} B(z) \, dz \right],$$

where $A(z) = 2z e^{-2z^2} B(z) = 2z e^{-2z^2 + 2s^2} \times x \equiv t/\tau_m$, $y \equiv \tau_m/(2\tau_0)$, and $s \equiv \tau_m(\tau_0 - \tau_m)/(2\tau_0\tau_m)$. The decay energy for $^{56}$Ni and $^{56}$Co are $\epsilon_{\text{Ni}} = 3.90 \times 10^{10}$ erg s$^{-1}$ g$^{-1}$ and $\epsilon_{\text{Co}} = 6.78 \times 10^9$ erg s$^{-1}$ g$^{-1}$, respectively (Sutherland & Wheeler 1984, Cappellaro et al. 1997). The decay times are $\tau_{\text{Ni}} = 8.77$ d and $\tau_{\text{Co}} = 111$ d. The time scale of the light curve is expressed as

$$\tau_m = \left( \frac{k_{\text{opt}}}{\beta c} \right)^{1/2} \left( \frac{10 M}{3 E_k} \right)^{1/4},$$

where $\beta \approx 13.8$ is an integration constant (Arnett 1982), $c$ is the speed of light, and $k_{\text{opt}}$ is the optical opacity, which stays constant in time for this modelling scheme. In reality, the opacity depends on the composition and temperature of the ejecta, therefore, it changes as the SN expands. Assuming a variable opacity, the models by Chugai (2003) for the bolometric light curve of SN 1998bw deliver an average value of 0.07 cm$^2$ s$^{-1}$ for the first 20 days after the explosion. The models by Mazzali et al. (2000) can reproduce the light curve of the type-Ic SN 1997ef at early times using a constant opacity of 0.08 cm$^2$ s$^{-1}$. With a constant opacity of 0.06 cm$^2$ s$^{-1}$, the synthetic light curves by Maeda et al. (2003) manage to reproduce the data of hypernovae at early phases. Thus, we chose a value of $k_{\text{opt}} = 0.07 \pm 0.01$ cm$^2$ s$^{-1}$, which includes within 1$\sigma$ the opacity values that have been employed in the literature.

Equations 1 and 2 are valid only for the photospheric phase ($t - t_0 \leq 40$ d). Given the lack of detections beyond day 40, no nebular component has been considered (see appendix in Valenti et al. 2008, for the complete model). The modelling procedure employed consists of a weighted $\chi^2$ minimisation, where $M_{\text{Ni}}$ and $M_{\text{ej}}/E_k$ are free. The latter will be dubbed the “timescale parameter” hereafter, because it approximates the light-curve shape (see Sect. 3.3 for details). To compute $M_{\text{ej}}$ and $E_k$ from the timescale parameter, we used the expression for the photospheric expansion velocity at maximum luminosity from Arnett (1982):

$$v_{\text{ph}}^2 \approx \frac{2E_k}{M_{\text{ej}}},$$

This quantity is critical to obtain reliable physical parameters of the explosion (Mazzali et al. 2013). A minimum expansion velocity of $\sim 14,000$ km s$^{-1}$ (SN 1998bw, Pian et al. 2006) and a maximum of $\sim 28,000$ km s$^{-1}$ (SN 2010bh; Bufano et al. 2012) have been measured for GRB-SNe. Thus, we employed $22,000 \pm 4,000$ km s$^{-1}$ if estimates of the photospheric velocity are not available. This conservative proxy encompasses with a 2$\sigma$ confidence the photospheric velocity of most spectroscopically-confirmed GRB-SNe at maximum luminosity (see, e.g., Bufano et al. 2012).

To calculate uncertainties, we performed thousand Monte-Carlo simulations for each event. Assuming Gaussian errors, each simulation consisted of a $\chi^2$ minimisation between the model with a randomised opacity and the randomised quasi-bolometric data points. From the resulting distributions for $M_{\text{Ni}}$ and $M_{\text{ej}}/E_k$, we obtain the median and the standard deviation (1$\sigma$). Then, eq. 3 is employed to compute $M_{\text{ej}}$ and $E_k$ propagating the errors accordingly. When using the wide range of expansion velocities for SN 2008hw and 2010ma, we computed the weighted average of $M_{\text{ej}}$ and $E_k$ between the parameters obtained using the minimum and maximum photospheric velocities as defined above, and listed the corresponding 1$\sigma$ ranges in Table 6. For SN 2009nz, Berger et al. (2011) measure an expansion velocity of 17,000 km s$^{-1}$ from Si ii 6355, which has been identified as a reliable tracer of the photospheric velocity (Sauer et al. 2006, Valenti et al. 2008). Although the date of the spectrum (16.3 rest-frame days after the GRB) coincides quite well with the maximum luminosity, the spectral coverage barely extends to 6250 Å and the spectrum has low S/N. Therefore, we assigned to this velocity a conservative uncertainty of 1.500 km s$^{-1}$, which corresponds to about 30 Å. The physical parameters and best-fit models are listed and plotted in Table 6 and Fig. 8 respectively.
Table 6. Physical parameters from quasi-bolometric light curves.

| SN          | $M_{Ni}$ [M$_\odot$] | $M_{ej}$ [M$_\odot$] | $E_k$ [10^51 erg] | $M_{ej}/E_k$ [10^51 M$_\odot$ erg^{-1}] | $\nu_{ph}$ [10^2 erg s^{-1}] | log $L_{max}$ | $t_{max}$ [days] | Reference |
|-------------|----------------------|----------------------|-------------------|----------------------------------------|-------------------------------|----------------|------------------|------------|
| 2008bw      | 0.39^{+0.04}_{-0.08} | 2.3^{+1.0}_{-0.7}    | 19 ± 15           | 0.7^{+0.7}_{-0.2}                     | 22 ± 4                        | 43.1 ± 0.3     | 12 ± 3            | 1          |
| 2009nz      | 0.50 ± 0.04          | 2.4^{+0.6}_{-0.3}    | 11 ± 4            | 1.2^{+0.6}_{-0.2}                     | 17 ± 5                        | 43.0 ± 0.2     | 18 ± 4            | 1          |
| 2010ma      | 0.43^{+0.03}_{-0.02} | 1.3^{+0.4}_{-0.3}    | 10 ± 6            | 0.20^{+0.09}_{-0.04}                  | 22 ± 4                        | 43.1 ± 0.2     | 10 ± 2            | 1          |
| 1998bw      | 0.38 ± 0.48          | 11 ± 3               | 50 ± 27           | 2.4 ± 0.2                              | 17 ± 1                        | 43.03 ± 0.01   | 17.8 ± 3          | 2.3        |
| 2003dh      | 0.25 ± 0.45          | 8 ± 4                | 40 ± 13           | 37 ± 1                                 | ~ 19                          | ~ 43.0 ± 17    | ~ 18 ± 4          | 1          |
| 2003lw      | 0.45 ± 0.65          | 13 ± 6               | 60 ± 37           | 37 ± 1                                 | ~ 18                          | ~ 43.2 ± 17    | ~ 18 ± 5          | 5          |
| 2006aj      | 0.21 ± 0.06          | 2 ± 2                | 2 ± 4             | 19 ± 1                                 | 42.99 ± 0.02                   | 8.8 ± 1        | 6.7              | 1          |
| 2010bh      | 0.21 ± 0.03          | 2.6 ± 0.2            | 24 ± 7            | 0.7 ± 0.3                              | 28                            | 42.63 ± 1      | 8.0 ± 9           | 8.9        |
| 2002ap      | 0.10 ± 0.10          | 2.5 ± 4              | 4 ± 3             | 14 ± 1                                 | ~ 11                          | ~ 42.4 ± 15    | ~ 11 ± 10         | 1          |
| 2003jd      | 0.36 ± 0.36          | 3 ± 7                | 7 ± 3             | 13.5 ± 1                               | ~ 17                          | ~ 42.9 ± 15    | ~ 17 ± 11         | 11         |
| 2007uy      | 0.30 ± 0.01          | 4.4 ± 0.3            | 15 ± 1            | 5.6 ± 1.0                              | 15.2                          | 42.83 ± 17     | 17.9 ± 12         | 12         |
| 2008D       | 0.07 ± 0.09          | 5.3 ± 1.0            | 6 ± 3             | 25 ± 1.7                               | ~ 10                          | ~ 42.4 ± 19    | ~ 19 ± 13         | 13, 14     |
| 2009bb      | 0.22 ± 0.06          | 4.1 ± 1.9            | 18 ± 7            | 3.8 ± 5.5                              | ~ 20                          | 42.8 ± 18      | ~ 18 ± 15         | 15         |

Notes. Different parts of the table correspond to GRB-SNe analysed here (top), further GRB-SNe (middle), and other SE SNe (bottom). Uncertainties are given at the 1σ level. The $\nu_{ph}$ values correspond to measurements as defined by eq. [5]. The log $L_{max}$ and $t_{max}$ values are estimated at the maximum bolometric luminosity, where $L_{max}$ is defined with respect to the explosion time.

References. (1) This paper, (2) Iwamoto et al. 1998, (3) Mazzali et al. 2003, (4) Mazzali et al. 2005, (5) Mazzali et al. 2006, (6) Pian et al. 2006, (7) Mazzali et al. 2006a, (8) Olivares E. et al. 2012, (9) Bufano et al. 2012, (10) Mazzali et al. 2005, (11) Valenti et al. 2008, (12) Kovalev et al. 2013, (13) Mazzali et al. 2008, (14) Tanaka et al. 2008, (15) Pignata et al. 2011.

4. Discussion

Regarding the NIR correction utilised in Sect. 3, we have to address that the extrapolation to SNe without data to SN 2002ap. Even though SN 2002ap was not preceded by a GRB, it was a type-Ic event that showed a maximum NIR fraction of about 0.6 of the total quasi-bolometric flux. Moreover, the colours of SN 2010ma turned out to be significantly bluer before $t < 20$ d than those of SN 1998bw. This could hint at a higher temperature of the SN envelope and, therefore, lower NIR fluxes. Therefore, we caution that there might be GRB-SNe that will not fit into our estimation of the NIR correction. The NIR fraction could have variations as large as ±0.15 if we compare SN 2002ap to SN 2007uy. This would translate into a maximum variation of about ±30% in the quasi-bolometric flux (equivalent to a 1σ error of ~10%) and therefore in the determinations of $M_{Ni}$. This issue could be solved in the future by using a larger sample, i.e., by including observations of new GRB-SNe in the NIR bands.

With the purpose of comparing the physical parameters computed by others for a set of different SNe, we gathered results from the literature in Table 3, although uncertainties were unfortunately not available for all. To compare the analytic method against the hydrodynamical simulations, we additionally computed the physical parameters of the explosion for SNe 1998bw and 2006aj using $\nu_{ph} = 17,000$ and 19,000 km s^{-1} (Pian et al. 2006), respectively. In Figure 7 we plotted the kinetic energy per unit mass $E_k/M_{ej}$ against the synthesised nickel mass $M_{Ni}$, a diagram that have been provided by Bufano et al. (2012). Even though some values have large uncertainties, we recognised a trend where the more energetic the SNe is, the more $^{56}$Ni it synthesises (Mazzali et al. 2007). We note also that hydrodynamical (green) and analytic (blue) measurements are consistent for SN 1998bw, despite showing significant differences for $M_{ej}$ and $E_k$ individually. This is because the ratio $E_k/M_{ej}$ is proportional to $\nu_{ph}^2$ (eq. [3]), which is a common measurement for both approaches. The discrepancies in $M_{ej}$ and $E_k$ individually are probably attributed to the different values used for the optical opacity and of course to the different assumptions and models employed (hydrodynamical or analytic). This would explain the large discrepancies shown for SN 2006aj as well, where the difference in $M_{Ni}$ could be explained by our inclusion of the NIR data. We caution that the physical parameters of the explosion might be highly model-depandent, especially the values obtained for $M_{ej}$ and $E_k$.

5. Summary and conclusions

Here we studied the GRB-SN connection by means of three individual events followed up in depth by XRT, UVOT, and GROND. The X-ray, UV, optical, and NIR data covered approximately six orders of magnitude in the radiative energy domain. Excluding $\gamma$-ray data, this represents a very comprehensive data set presented for the associations GRB 081007/SN 2008bw, GRB 091127/SN 2009nz, and GRB 101219B/SN 2010ma.

In Sect. 3 the light curves of the three events are thoroughly analysed. The host-galaxy extinction along the line of sight of each event is computed from the broad-band SED. The light curves of individual filter bands are modelled with SN 1998bw templates (Sect. 3.1). The AG component is subtracted to isolate the SN counterpart. The NIR flux was estimated from the data of five SE SNe and using BB fits of the optical data. This correction has been applied to the integrated optical flux of our rebrightenings to obtain quasi-bolometric light curves from 340 to 2200 nm. We note that the NIR contribution of SN 2002ap is 10–15% larger than that of the GRB-SNe 1998bw and 2006aj.
Moreover, the colours of SN 2010ma at early times are bluer than those of SN 1998bw suggesting lower NIR fluxes for this object. Therefore, we conclude that more NIR data is needed to constrain better the NIR contribution in GRB-SN light curves. Using an analytic model for bolometric light curves, the physical parameters of the SN explosion were computed for each event analogous to the case of SN 2010bh in Olivares E. et al. (2012). We also computed the nickel mass against the envelope energy per unit mass (see Table 6) and plotted the weighted centre of the range. We caution that while green squares depict values obtained via hydrodynamical simulations, blue circles correspond to parameters measured using the analytic approach explained in Sect. 3.3 or similar. When ranges are given in Table 6, we plotted the weighted centre of the range. We caution that both by the Deutscher Akademischer Austausch Dienst (DAAD) and the Coordination (CUP), 169–190.

References

Arnett, D. 1996, Supernovae and Nucleosynthesis (New York: University Press)

Arnett, W. D. 1982, ApJ, 253, 785

Baade, W. & Zwicky, F. 1934, Physical Review, 46, 76

Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, Space Sci. Rev., 120, 143

Baumgartner, W. H., Cummings, J. R., Evans, P. A., et al. 2008, GCN Circ., 8330, 1

Berg, E., Chornock, R., Holmes, T. R., et al. 2011, ApJ, 743, 204

Berger, E., Fox, D. B., Cucchiara, A., & Conko, S. B. 2008, GCN Circ., 8335, 1

Beuermann, K., Hessman, F. V., Reinsch, K., et al. 1999, A&A, 352, L26

Bloom, J. S., Kulkarni, S. R., Price, P. A., et al. 2002, ApJ, 572, L45

Bolzonella, M., Murailles, J.-M., & Peller, R. 2000, A&A, 363, 476

Bromberg, O., Nakar, E., Piran, T., & Sari, R. 2012, ApJ, 749, 110

Buicantinii, N., Quataert, E., Metzger, B. D., et al. 2009, MNARS, 396, 2038

Bufano, F., Pian, E., Sollerman, J., et al. 2012, ApJ, 753, 67

Burrows, A. 2000, Nature, 403, 727

Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, Space Sci. Rev., 120, 165

Cano, Z. 2013, MNARS, 434, 1098

Cano, Z. 2014, ApJ, 794, 121

Cano, Z., Bersier, D., Guidorzi, C., et al. 2011, ApJ, 740, 41

Cano, Z., de Ugarte Postigo, A., Pozanenko, A., et al. 2014, arXiv:1405.3114

Cano, Z. & Jakobsson, P. 2010c, ApJ, 718, L150

Colgate, S. A., Petscheck, A. G., & Kriese, J. T. 1980, ApJ, 237, L81

Covino, S., Melandri, A., Salvaterra, R., et al. 2013, MNARS, 432, 121

Cucchiari, A., Fox, D., Levan, A., & Tanvir, N. 2009, GCN Circ., 10202, 1

Cummings, J. R., Barthelmy, S. D., Baumgartner, W. H., et al. 2010, GCN Circ., 11475, 1

de Ugarte Postigo, A., Cano, Z., Thonne, C. C., et al. 2013, CBET, 3637, 1

de Ugarte Postigo, A., Thonne, C. C., & Gorosabel, J. 2012, GCN Circ., 12802, 1

Della Valle, M., Benetti, S., Mazzali, P., et al. 2008, CBET, 1602, 1

Della Valle, M., Malesani, D., Benetti, S., et al. 2003, A&A, 406, L33

Della Valle, M., Malesani, D., Bloom, J. S., et al. 2006, ApJ, 642, L103

Dessart, L. & Hillier, D. J. 2005, A&A, 439, 671

Dessart, L., Hillier, D. J., Waldman, R., Livne, E., & Blondin, S. 2012, MNARS, 426, L76

Ferrero, P., Kann, A. D., Zeh, A., et al. 2006, A&A, 457, 857

Filippenko, A. V. 1997, ARA&A, 35, 309

Folatelli, G., Bersten, M. C., Kuncarayakti, H., et al. 2014, ApJ, 792, 7

Foley, R. J., Papenkova, M. S., Swift, B. J., et al. 2003, PASP, 115, 1220

Fryer, C. L., Hungerford, A. L., & Young, P. A. 2007, ApJ, 662, L55

Greiner, J., Bornemann, W., Clemens, C., et al. 2007, The Messenger, 130, 12

Greiner, J., Krühler, T., Klose, S., et al. 2011, A&A, 526, A30

Greiner, J., Klose, S., Salvato, M., et al. 2003, ApJ, 599, 1223

Greiner, J., Kühlker, T., Klose, S., et al. 2011, A&A, 526, A30

Hanssen, B. M. S. 1999, ApJ, 512, L117

Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288

Heise, J., in’t Zand, J., Kippen, R. M., & Woods, P. M. 2001, in Gamma-ray Bursts in the Afterglow Era, ed. E. Costa, F. Frontera, & J. Hjorth, ESO Astrophysics Symposia (Rome, Italy: Springer-Verlag), 16

Hjorth, J. & Bloom, J. S. 2012, The Gamma-Ray Burst - Supernova Connection (CUP), 169–190.

Hjorth, J., Sollerman, J., Møller, P., et al. 2009, Nature, 423, 847

Iwamoto, K., Mazzali, P. A., Nomoto, K., et al. 1998, Nature, 395, 670

Jin, Z.-P., Covino, S., Della Valle, M., et al. 2013, ApJ, 774, 114

Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775

Kann, D. A., Klose, S., Zhang, B., et al. 2011, ApJ, 734, 96

Kann, D. A., Klose, S., Zhang, B., et al. 2010, ApJ, 720, 1513

The nickel mass against the envelope energy per unit mass.

While green squares depict values obtained via hydrodynamical simulations, blue circles correspond to parameters measured using the analytic approach explained in Sect. 3.3 or similar. When ranges are given in Table 6, we plotted the weighted centre of the range. We caution that while green squares depict values obtained via hydrodynamical simulations, blue circles correspond to parameters measured using the analytic approach explained in Sect. 3.3 or similar. When ranges are given in Table 6, we plotted the weighted centre of the range. We caution that...
Appendix A: Optical/NIR photometry

The three Tables presented as follows are corrected for Galactic foreground extinction (Schlegel et al. 1998).

Table A.1. GRB 081007/SN 2008hw.

| $t - t_0$ | $\Delta t^a$ | $g'$ | $r'$ | $i'$ | $z'$ | $t - t_0$ | $\Delta t$ | $J$ | $H$ | $K_s$ |
|-----------|-------------|-----|-----|-----|-----|-----------|-------------|-----|-----|-----|
| [d] | [ks] |          |     |     |     | [d] | [ks] |     |     |     |
| 0.013 | 0.39 | 17.25(16) | 17.28(11) | 17.14(09) | 17.02(08) | 0.013 | 0.40 | 17.22(05) | 16.76(03) | 16.56(05) |
| 0.018 | 0.40 | 17.51(16) | 17.53(11) | 17.37(09) | 17.29(08) | 0.019 | 0.42 | 17.53(05) | 17.06(03) | 16.82(04) |
| 0.025 | 0.69 | 17.77(16) | 17.78(11) | 17.64(09) | 17.53(07) | 0.026 | 0.75 | 17.77(05) | 17.28(03) | 17.05(04) |
| 0.035 | 0.70 | 17.99(16) | 17.92(11) | 17.85(09) | 17.76(08) | 0.035 | 0.76 | 17.98(05) | 17.44(05) | 17.26(04) |
| 0.050 | 1.74 | 18.28(16) | 18.18(11) | 18.11(09) | 17.96(07) | 0.050 | 1.79 | 18.16(05) | 17.70(03) | 17.51(04) |
| 0.071 | 1.75 | 18.51(16) | 18.48(11) | 18.34(09) | 18.25(07) | 0.071 | 1.80 | 18.39(05) | 17.94(04) | 17.74(04) |
| 0.092 | 1.72 | 18.68(16) | 18.67(11) | 18.57(09) | 18.50(07) | 0.092 | 1.77 | 18.58(05) | 18.10(04) | 17.90(05) |
| 0.912 | 2.53 | 20.42(16) | 20.29(13) | 20.15(10) | 20.03(08) | 0.902 | 0.75 | 20.11(07) | > 19.41 | > 19.16 |
| 3.807 | 1.73 | 22.00(34) | 22.09(27) | 21.99(28) | 21.88(28) | 0.917 | 1.79 | 20.20(06) | 19.59(10) | 19.54(10) |
| 10.85 | 5.33 | > 23.46 | 23.32(15) | 22.99(23) | 23.17(25) | 3.808 | 1.78 | > 20.96 | > 20.03 | > 19.24 |
| 15.91 | 5.32 | > 23.87 | 23.17(20) | 23.20(35) | > 22.43 | 10.85 | 5.37 | > 21.67 | > 20.84 | > 19.44 |
| 18.83 | 7.17 | > 23.76 | 23.27(30) | 22.97(32) | 22.76(31) | 15.91 | 5.38 | > 21.67 | > 20.76 | > 19.83 |
| 22.86 | 7.11 | > 24.03 | 23.51(25) | 23.45(38) | 23.15(36) | 18.83 | 7.21 | > 21.15 | > 19.67 | > 19.62 |
| 28.89 | 3.53 | > 23.29 | > 22.78 | > 22.18 | > 21.12 | 22.86 | 7.16 | > 21.43 | > 20.69 | > 20.00 |

Notes. The GRB trigger time is $t_0 = 54746.225$ MJD. All data corrected for $A_{\text{host}} = 0.68 \pm 0.08$ mag (SMC). Image subtraction of the host was performed for $g'r'i'z'$. (a) The duration of the observation.

Table A.2. GRB 091127/SN 2009nz.

| $t - t_0$ | $\Delta t^a$ | $g'$ | $r'$ | $i'$ | $z'$ | $t - t_0$ | $\Delta t$ | $J$ | $H$ |
|-----------|-------------|-----|-----|-----|-----|-----------|-------------|-----|-----|
| [d] | [ks] |          |     |     |     | [d] | [ks] |     |     |
| 1.075 | 1.55 | 19.69(03) | 19.50(05) | 19.37(03) | 19.17(01) | 1.070 | 0.75 | 19.04(08) | 18.81(09) |
| 1.260 | 0.69 | 19.94(03) | 19.77(03) | 19.69(03) | 19.46(03) | 1.243 | 1.75 | 19.23(06) | 18.99(07) |
| 2.079 | 1.70 | 20.81(04) | 20.58(04) | 20.47(01) | 20.38(02) | 2.080 | 1.75 | 20.09(09) | 19.86(10) |
| 2.198 | 1.71 | 20.88(03) | 20.65(04) | 20.54(03) | 20.41(03) | 2.198 | 1.77 | 20.09(07) | 19.90(12) |
| 3.207 | 1.71 | 21.64(07) | 21.32(04) | 21.26(05) | 21.13(05) | 3.207 | 1.76 | 20.54(32) | 20.52(22) |
| 4.212 | 1.70 | 22.10(09) | 21.87(06) | 21.85(10) | 21.60(07) | 4.212 | 1.75 | 20.88(18) | 20.99(28) |
| 6.175 | 1.71 | 22.68(13) | 22.40(10) | 22.51(14) | 22.22(10) | 6.175 | 1.75 | 21.53(31) | > 21.26 |
| 11.10 | 1.71 | 23.76(12) | 22.76(06) | 22.50(10) | 22.86(13) | 11.10 | 1.75 | > 21.63 | > 21.16 |
| 23.17 | 0.34 | > 22.87 | 22.85(23) | > 22.05 | > 22.15 | ... | ... | ... | ... |
| 46.13 | 3.92 | > 24.43 | 24.08(13) | 23.58(27) | 23.20(22) | 46.13 | 3.97 | 21.74(27) | > 21.35 |
| 49.12 | 1.70 | > 24.69 | 24.49(32) | > 23.41 | 23.28(26) | 49.12 | 1.75 | > 21.69 | > 21.19 |
| 54.09 | 1.90 | > 21.26 | > 23.88 | > 18.86 | > 22.51 | 54.09 | 1.75 | > 21.37 | > 20.93 |

Notes. The GRB trigger time is $t_0 = 55162.976$ MJD. Data not corrected for negligible $A_{\text{host}} < 0.03$ mag (LMC). Image subtraction of the host was performed for $g'r'i'z'$. (a) The duration of the observation.
Appendix B: Sequences of standard stars

The sequence of reference stars in the field of GRB 091127/SN 2009nz are taken from Filgas et al. (2011). Stars from the 2MASS catalogue (Skrutskie et al. 2006) are used for the $JHK_s$ bands.

Table B1. Reference stars in the field of GRB 081007/SN 2008hw.

| RA       | Dec. | $g'$ | $r'$ | $i'$ | $z'$ |
|----------|------|------|------|------|------|
| 339.91132 | -40.14995 | 19.334 ± 0.013 | 18.940 ± 0.011 | 18.795 ± 0.016 | 18.658 ± 0.017 |
| 339.91385 | -40.15378 | 19.050 ± 0.011 | 18.495 ± 0.007 | 18.274 ± 0.012 | 18.075 ± 0.012 |
| 339.92912 | -40.17095 | 14.897 ± 0.001 | 14.399 ± 0.001 | 14.220 ± 0.001 | 14.091 ± 0.001 |
| 339.94805 | -40.15434 | 19.887 ± 0.020 | 19.147 ± 0.011 | 18.807 ± 0.016 | 16.641 ± 0.018 |
| 339.95393 | -40.11101 | 19.971 ± 0.020 | 19.201 ± 0.012 | 18.807 ± 0.016 | 16.641 ± 0.018 |
| 339.97304 | -40.11895 | 19.890 ± 0.019 | 19.201 ± 0.012 | 18.807 ± 0.016 | 16.641 ± 0.018 |
| 339.97329 | -40.17987 | 19.631 ± 0.016 | 18.129 ± 0.006 | 16.949 ± 0.005 | 16.399 ± 0.004 |
| 339.98310 | -40.12094 | 19.542 ± 0.015 | 18.780 ± 0.009 | 18.488 ± 0.013 | 16.309 ± 0.014 |
| 339.99130 | -40.17932 | 17.947 ± 0.005 | 17.691 ± 0.004 | 17.588 ± 0.007 | 17.517 ± 0.007 |

Notes. All are observed magnitudes in the AB system.

Table B2. Reference stars in the field of GRB 101219B/SN 2010ma.

| RA       | Dec. | $g'$ | $r'$ | $i'$ | $z'$ |
|----------|------|------|------|------|------|
| 12.22124 | -34.52946 | 22.85 ± 0.10 | 19.87 ± 0.05 | 18.365 ± 0.019 | 17.720 ± 0.018 |
| 12.25499 | -34.54326 | 19.021 ± 0.031 | 18.006 ± 0.011 | 17.568 ± 0.012 | 17.368 ± 0.015 |
| 12.26985 | -34.56368 | 21.02 ± 0.07 | 19.519 ± 0.034 | 18.475 ± 0.022 | 18.088 ± 0.025 |
| 12.22871 | -34.56753 | 15.350 ± 0.003 | 14.928 ± 0.002 | 14.772 ± 0.002 | 14.674 ± 0.003 |
| 12.24608 | -34.57123 | 17.328 ± 0.010 | 17.099 ± 0.006 | 17.017 ± 0.009 | 16.970 ± 0.011 |
| 12.21783 | -34.57419 | 20.41 ± 0.06 | 19.226 ± 0.029 | 18.663 ± 0.026 | 18.484 ± 0.039 |
| 12.26934 | -34.58304 | 16.972 ± 0.007 | 16.599 ± 0.004 | 16.446 ± 0.006 | 16.398 ± 0.007 |
| 12.25056 | -34.58787 | 16.996 ± 0.007 | 15.583 ± 0.003 | 14.623 ± 0.002 | 14.166 ± 0.002 |
| 12.21137 | -34.59066 | 18.380 ± 0.017 | 18.173 ± 0.013 | 18.097 ± 0.016 | 18.125 ± 0.027 |

Notes. All are observed magnitudes in the AB system.
Appendix C: Blackbody fits

Here we present the blackbody fits for the analysed GRB-SNe, which were utilised to estimate the NIR contribution (Sect. 3.3.1).

Fig. C.1. Blackbody fits to the optical photometry of SN 2008hw. Colour temperatures are about 5,000 K. Points with only a lower error bar are upper limits. The blue shaded region shows the area between the 1σ contours, where the central line is the best fit.

Fig. C.2. Blackbody fits to the optical photometry of SN 2009nz. Colour temperatures evolve from ∼ 7,000 to ∼ 4,000 K approximately. Point, line, and region coding are the same as in Fig. C.1.
Fig. C.3. Blackbody fits to the optical photometry of SN 2010ma. Colour temperatures evolve from $\sim 6,000$ to $\sim 4,000$ K. Point, line, and region coding are the same as in Fig. C.1.