VLT Observations of GRB-Supernovae

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Abstract. I review the observational status of the Supernova/Gamma-Ray Burst connection. Observations of long duration Gamma-ray bursts suggest that they are associated with bright, broad-lined SNe-Ic.However recent observations of GRB 060614 and XRF 080109 puzzle this scenario, pointing out the existence of a great variety of SN-GRB explosions: GRBs/XRFs associated with very faint SNe and bright SNe-Ib associated with exceptionally faint XRFs (failed GRBs).

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INTRODUCTION

Observations of Gamma-ray Bursts (GRBs) from space and ground-based telescopes have established the existence of a link between long-duration GRBs and the death of massive stars. This conclusion is based on several pieces of evidence:

i) the discovery of four associations between "broad lined" Supernovae Ic (i.e. SNe-Ic characterized by a large kinetic energy, often labeled as hypernovae, HNe hereafter) and GRBs: GRB 980425/SN 1998bw (Galama et al. 1998), GRB 030329/SN 2003dh (Stanek et al. 2003, Hjorth et al. 2003), GRB 031203/SN 2003lw (Malesani et al. 2004) and GRB 060218/SN 2006aj (Campana et al. 2006; Pian et al. 2006);

ii) in three cases, spectroscopic observations of the rebrightenings observed during the late decline of the afterglows (Bloom et al. 1999) have revealed the presence of SN features, in GRB 021211/SN 2002lt (Della Valle et al. 2003), in XRF 020903 (Soderberg et al. 2005), and possibly in GRB 050525A/SN 2005nc (Della Valle et al. 2006a);

iii) the host galaxies of long GRBs are star forming galaxies (Djorgovski et al. 1998, Fruchter et al. 2006, Modjaz et al. 2008a).

Several theoretical scenarios (e.g. MacFadyen & Woosley; Nomoto et al. 2007) suggest that long duration GRBs are produced in the collapse of the core of Wolf-Rayet (H/He stripped-off) stars, with an initial mass higher than $\sim 30\ M_\odot$ and a bright SNe-Ic is the final product. Indeed a progenitor of the size of a W-R star has been observed for GRB 060218 (Campana et al. 2006). However, recent observations of GRB 060614 (Della Valle et al. 2006b, Fynbo et al. 2006, Gal-Yam et al. 2006) and SN 2008D/XRF 080109 (Malesani et al. 2008, Modjaz et al. 2008b, Soderberg et al. 2008, Mazzali et al. 2008) puzzle this scenario: on one side there are some long-duration GRBs without an accompanying (bright) SN, on the other one it looks like that some

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“broad-lined” SNe with energy budgets (luminous and kinetic) definitely “above the average” (e.g. SN 2008D), are not able to produce a GRB.

NEARBY GRB-SN ASSOCIATIONS

GRB 980425 was discovered in ESO 184-G82 at $d = 40Mpc$ and it was underenegetic by 4 orders of magnitudes with respect to the “cosmological” standard reservoir of about 10^{51} erg. The associated SN, 1998bw, was very bright at maximum ($M_V \sim -19$) and the ejecta exhibited unusual high expansion velocities (about 30,000 km/s) when compared to “standard SNe-Ib/c” (Patat et al. 2001). The radio emitting region associated with the GRB-SN was expanding at mildly relativistic velocities ($\Gamma \sim 2$, Kulkarni et al. 1998). Maeda et al. (2006) have recently modeled the bolometric lightcurve of SN 1998bw with a relatively small amount of ^{56}Ni ($\sim 0.4\ M_\odot$) by assuming that the SN explosion was highly asymmetric (see also Höflich, Wheeler & Wang 1999). The former authors derive a mass for the progenitor of SN 1998bw, on the main sequence, of $\sim 40M_\odot$

GRB 030329 was discovered by the HETE–2 satellite at a redshift $z = 0.1685$ (Greiner et al. 2003). The spectroscopic evolution of the associated SN 2003dh was similar to SN 1998bw (Stanek et al. 2003, Hjorth et al. 2003; Kawabata et al. 2003; Matheson et al. 2003). Both the gamma-ray energy budget and afterglow properties of this GRB were similar to those observed in “cosmological GRBs”, and therefore, the link between GRBs and SNe was finally established to be more general. The progenitor was a massive envelope-stripped star of $\sim 30-40M_\odot$ on the main sequence (Mazzali et al. 2003).

GRB 031203 was a 30s burst detected by INTEGRAL (Mereghetti et al. 2003) at $z = 0.1055$ (Prochaska et al. 2004, Margutti et al. 2007). The burst energy was of $\sim 10^{49}$ erg, well below the “standard reservoir” of $\sim 10^{51}$ erg of “cosmological” GRBs (Frail et al. 2001, Panaitescu & Kumar 2001). A few days after the GRB, a rebrightening was apparent in all optical bands (Thomsen et al. 2004; Cobb et al. 2004; Gal-Yam et al. 2004). Spectra of the rebrightening obtained 14 and 23 rest-frame days after the GRB (see Fig. 1) are remarkably similar to those of SN 1998bw obtained at comparable epochs (Malesani et al. 2004). SN 2003lw was possibly brighter than SN 1998bw by 0.3 mag. However some words of caution are in order, given the large uncertainty (about 0.3 mag) with affects the correction for reddening. The theoretical modeling of the photometric and spectroscopic evolution indicates that the progenitor had a main sequence mass of $\sim 40M_\odot$ (Mazzali et al. 2006).

GRB 060218 was detected by Swift at z=0.033. This burst was unusually long, with $T_{90} \sim 2100s$. The UVOT telescope found an emission peaking in a broad plateau first at UV wavelengths and later in the optical. The lightcurve showed a minimum at about 200 ks after the gamma event and a rebrightening peaking at about 700 ks (due to the Ni-Co-Fe decay). A few days after the Swift observations, low resolution spectra (Pian et al. 2006) pointed out the presence of a rising SN (2006aj) with broad emission lines similarly to those observed in other GRB-SNe. The most striking feature exhibited by this gamma event (see Campana et al. 2006) is the presence of a thermal component observed in the XRT data, up to 10 ks, and in the UVOT data, up to about 100 ks. This

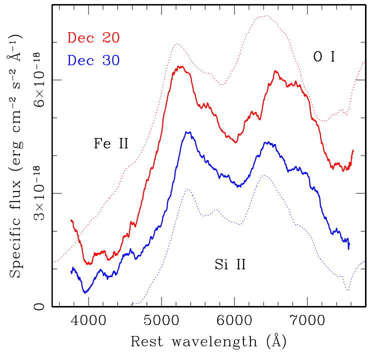

FIGURE 1. Spectra of SN 2003lw, taken on 2003 December 20 and 30 (solid lines), smoothed with a boxcar filter 250Å wide. Dotted lines show the spectra of SN 1998bw taken on 1998 May 9 and 19 (13.5 and 23.5 days after the GRB, or 2 days before and 7 days after the V-band maximum, respectively), extinguished with $E(B-V) = 1.1$ and a Galactic extinction law. The spectra of SN 1998bw were vertically displaced for presentation purposes (plot from Malesani et al. 2004).

black body component shows a decreasing temperature accompanied by an increasing luminosity, which implies an increase in the apparent emission radius from 5×10^{11} cm to about 3×10^{14} cm, in about 100ks. This corresponds to an expansion velocity of the order of 30,000 km/s, which is quite typical for GRB-SNe. After assuming linear expansion one can estimate the star radius of the progenitors to be of the order of 5×10^{11} cm which is comparable to the size of a Wolf-Rayet star. The (UV) black-body component has been interpreted in terms of a shock break-out wave emerging from the region, around the progenitor star, within which the stellar wind (from the massive progenitor) is optically thick.

SN/GRB ASSOCIATIONS AT HIGH Z

GRB 021211 was detected by the HETE–2 satellite at $z = 1.006$ (Vreeswijk et al. 2002). Late-time photometric follow-up, carried out with the ESO VLT–UT4, together with HST observations, show a rebrightening, starting ~ 15 days after the burst and reaching the maximum ($R \sim 24.5$) during the first week of January (see Fig. 2). A spectrum of the afterglow + host obtained at VLT during the rebrightening showed broad low-amplitude undulations blueward and redward of a broad absorption, the minimum of which was measured at ~ 3770 Å (in the rest frame of the GRB), whereas its blue wing extends up to ~ 3650 Å (Della Valle et al. 2003). The comparison with the spectra of other SNe supports the identification of the broad absorption with a blend of the Ca II H and K absorption lines (Fig. 3). The blueshift corresponding to the minimum of the absorption implies an expansion velocity of $v \sim 14000$ km/s, which is often observed in SN explosions.

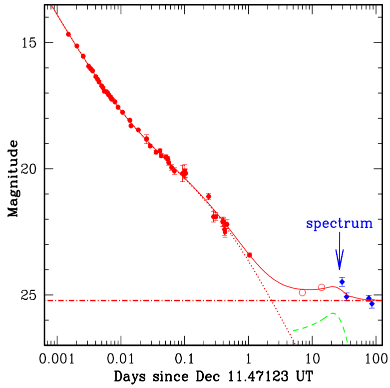

FIGURE 2. Light curve of the afterglow of GRB 021211. Filled circles represent data from literature, open circles are converted from HST measurements, while filled diamonds indicate our data; the arrow shows the epoch of our spectroscopic measurement. The dotted and dot-dashed lines represent the afterglow and host contribution respectively. The dashed line shows the light curve of SN 1994I reported at $z = 1.006$ and dereddened with $A_V = 2$. The solid line shows the sum of the three contributions (plot from Della Valle et al. 2003).

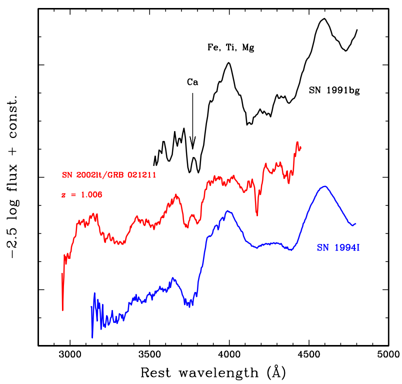

FIGURE 3. Spectrum of the afterglow+host galaxy of GRB 021211 (middle line) taken on Jan 8.3 UT (27 days after the burst). For comparison, the spectra of SN 1994I (Ic) and SN 1991bg (Ia) are displayed, both showing the Ca absorption. Adapted from Della Valle et al. 2003.

The long-duration GRB 050525A was discovered by the *Swift* satellite on 2005 May 25.002 UT. Given the fluence $\mathscr{F} = (2.01 \pm 0.05) \times 10^{-5}$ erg cm^{-2}, the duration $T_{90} = 8.8 \pm 0.5$ s and the redshift $z = 0.606$, it was a bright event ($E_{iso} = 5.4 \times 10^{52}$ erg). Photometric data show a flattening of the light curve at $R \sim 24$, starting about 5 d after the burst (observer rest frame) and lasting for about 20 d. The contribution of the host galaxy to the “plateau” luminosity is estimated to be $\sim 40\%$, The afterglow contribution, as extrapolated from the earlier measurement, is negligible at these epochs ($< 3\%$ at 20 d after the GRB). This fact suggests that the flattening is powered by an additional source of energy (Della Valle et al. 2006a). A spectrum, obtained at the VLT-UT1 with the FORS 2 36 d after the burst (observer frame) shows some similarities with the spectrum of SN 1998bw obtained 5d past maximum and dimmed by ≈ 0.9 mag. However the low S/N ratio of the spectrum obtained at VLT does not allow us to rule out alternate interpretations such as a light-echo.

GRB RATES

After combining the local density of B luminosity (e.g. Madau, Della Valle & Panagia 1998) with the rate of 0.16 SNe-Ibc per century and per 10^{10} $L_{B,\odot}$ (SNu units, Cappellaro, Evans & Turatto 1999), we find a rate of SNe-Ibc in Sbc–Irr galaxies of $\sim 2\times10^4$ SNe-Ibc Gpc^{-3} yr^{-1}. This figure has to be compared with the rate of "cosmological" GRBs of ~ 1 GRB Gpc^{-3} yr^{-1} (Guetta, Piran & Waxman 2005, Schmidt 2001), rescaled for the jet beaming factor, f_b^{-1}: ~ 75 (Guetta, Piran & Waxman 2005) up to ~ 500 (Frail et al. 2001), corresponding to beaming angles $\sim 10^\circ$– 4° respectively. Taking these figures at their face value, we find the ratio GRB/SNe to be in the range: $\sim 0.4\% - 3\%$ (see Della Valle 2006c, Guetta & Della Valle 2007). Radio surveys give an independent and consistent constraint of GRB/SNe-Ibc $< 10\%$ (Soderberg et al. 2006a). Since the volume sampled by sub-energetic GRBs is much smaller than that probed by cosmological GRBs (a factor $\sim 10^6$) the frequency of occurrence of sub–energetic GRBs may well be higher by several orders of magnitude. However, Guetta & Della Valle (2007) have found that sub-energetic GRBs are, on average, much less collimated events than "cosmological" GRBs, likely $\mathrm{f}_b^{-1} \lesssim 10$, (see also Soderberg et al. 2006b), therefore the discrepancy between the intrinsic frequency of occurence of "cosmological" and "local" GRBs may be considerably smaller, possibly of the order of a factor of ~ 3. Given the uncertainties, one cannot exclude that a single population of progenitors is responsible for producing both sub-energetic/isotropic and highly beamed GRBs.

SPLASHY GRBS AND SILENT SUPERNOVAE

Recent observations of GRB 060614 (Della Valle et al. 2006b, Fynbo et al. 2006, Gal-Yam et al. 2006) challenge the simple idea that all long-duration GRBs are produced in bright SN-Ibc explosions. Indeed any "potential" SN associated with this GRB was about 200 times fainter (in R band) than the other GRB-SNe (see Fig. 4). This fact may suggest scenarios in which some long duration GRBs are produced during merging events between compact remnants of the stellar evolution (similarly to "short" GRB scenarios, e.g. Gherels et al. 2006, but see Amati et al. 2007 for a different view) or it calls for other scenarios such as the vacuum polarization mechanism (Ruffini 1998), the transition neutron star to quark star (Berezhiani et al. 2003), and the "Supranova" model (Vietri & Stella 1999). Della Valle et al. 2006b proposed as possible explanation for the lack of a bright SN associated with GRB 060614 that most ^{56}Ni produced during the late stages of the stellar evolution of the progenitor is not ejected with the envelopes, as commonly observed in the GRB-SNe, but it falls back into the new-born black-hole.

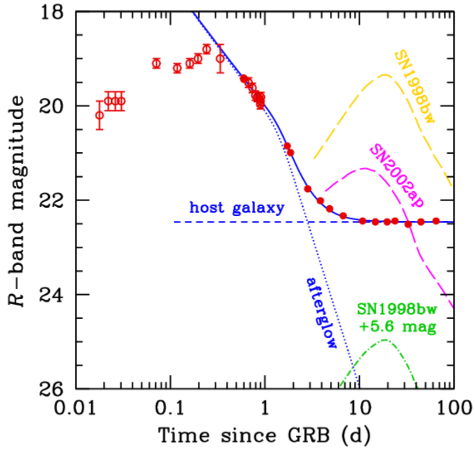

FIGURE 4. Light curve of the optical emission from GRB 060614. The circles represent the observed data. There is no sign of rebrightening due to a supernova. The light curve after 0.3 day (blue solid line) has been decomposed in the sum of two components: the afterglow (blue dotted line) and the host galaxy (blue short-dashed lines). There is no need for a supernova component: the green dot-dashed line is the faintest supernova allowed by our data. For comparison, the long-dashed lines show the light curves of two supernovae: SN 1998bw, the proto-typical event associated with a GRB, and SN 2002ap, which is a faint broad-lined SN-Ib/c (adapted from Fig. 2 of Della Valle et al. 2006b).

As a consequence only the tiny fraction of ^{56}Ni in the jets, less than $\sim 10^{-4/-5}$ $M_{\odot}$, can escape from the exploding progenitor (see Tominaga et al. 2007, Nomoto et al. 2007). The presence of a so small amount of ^{56}Ni in the ejecta can explain the very low luminosity ($M_B \lesssim -13$) of the possible SN associated with this GRB. This scenario is supported by the recent discovery of a class of extraordinary faint core-collapse SNe (Pastorello et al. 2007 and references therein).

SPLASHY SUPERNOVAE AND (ALMOST) SILENT GRBS

On 2008 January 9.57 UT the X-Ray Telescope (XRT) on board Swift detected a weak X-ray Flash (XRF 080109) (Berger & Soderberg 2008) in the galaxy NGC 2770 (Thöne et al. 2008). Optical follow-up revealed the presence of a supernova coincident with the XRF, SN 2008D and early spectra showed broad absorption lines superposed on a blue continuum, and lacked hydrogen or helium lines (Malesani et al. 2008, Valenti et al. 2008) typical of broad-lined SN Ic. Particularly the spectra resembled those of the XRF-SN 2006aj (Pian et al. 2006) or the non-GRB HN SN 2002ap (Mazzali et al. 2002) though much more reddened ($E(B-V)_{tot} = 0.65$ mag).

In addition to the weak XRF, SN 2008D shows a number of novel features. First of all the optical light curve had two peaks: a first, maximum ($V \approx 18.4$) was reached 2 days after the XRF. After a brief decline the luminosity increased again, reaching principal maximum ($V = 17.37$) ~ 20 days after the XRF. The first dim optical peak was only seen in two other type Ib SNe, SN 1999ex (Stritzinger et al. 2002) and SN 2005bf (Folatelli et al. 2006). Finally, unlike SNe 2006aj and 2002ap, the broad absorptions did not persist. As they disappeared, He I lines developed (Modjaz et al. 2008c) then displaying a narrow-lined, Type Ib spectrum.

Mazzali et al. (2008) have reproduced the spectral evolution and the light curve of SN 2008D (after the first narrow peak) using a spherically symmetric expansion model, characterized by $E \sim 6 \cdot 10^{51}$ erg and with $M_{\rm ej} \sim 7 M_{\odot}$. The progenitor had a main sequence mass $\sim 30 M_{\odot}$. A star of this mass is likely to collapse to a black hole, as do GRB/SNe (MacFadyen & Woosley 1999, Nomoto et al. 2007). However, all GRB-SNe initially had velocities higher than SN 2008D or SN 2002ap and never showed helium. Had the He layer not been present in SN 2008D, the explosion energy would have accelerated the inner core to higher velocities, and broad lines may have survived.

According to Mazzali et al. (2008) these data provide the empirical grounds for an explanation of SN 2008D/XRF 080109, which is alternative to the shock break-out scenarios proposed by other authors (Soderberg et al. 2008, Chevalier & Fransson 2008; Modjaz et al. 2008b, see also Xu et al. 2008 and Li-Xin 2008 for different views). XRF 080109 may have been the breakout of a failed relativistic jet powered by a central engine as in GRBs. The jet failed because its energy was initially low or because it was damped by the He layer, which is absent in GRB-HNe, or both. The weakness of the jet resulted in the low X-ray flux and the small amount of material ($\sim 0.03 M_{\odot}$ according to Mazzali et al. 2008) with $v > 0.1c$. This scenario implies that GRB-like inner engine activity exists in all black hole-forming SNe Ibc (Maeda et al. 2006). SN 2008D had significantly higher energy than normal core-collapse SNe, although less than GRB/HNe. Therefore, it is unlikely that all SNe Ibc, and even more so all core-collapse SNe produce weak X-ray flashes similar to XRF 080109. On the contrary it is very likely that for less massive stars that still collapse to a black hole producing a less energetic explosion (e.g. SN 2002ap) no jet may emerge at all. Finally, progenitor stars that only collapse to a neutron star are not expected to have jets. In this framework SN 2008D links events, like GRB-SNe and normal “core-collapse” SNe, that are physically related but have different observational properties.

CONCLUSIONS

A decade of GRB observations have produced an amazing advance in our understanding of the GRB-SN phenomenon and a number of important results do emerge:

i) Long duration GRBs originates from the death of massive stars. This fact is well documented by: a) the direct observations of bright SNe-Ic associated with GRBs; b) a dozen of rebrightenings, detected during the late stages of the afterglows, which are well reproduced by adding SN components to the afterglow lightcurves. In some cases SN features have been detected in the spectra of the “bumps”; c) most host galaxies of long GRBs exhibit an intense star forming activity.

ii) Observations of GRB 060218 coupled with simple theoretical arguments indicate that the progenitor star of the associated SN (2006aj) had a radius of about $\sim 5 \times 10^{11}$

cm. This is similar to the size of a Wolf-Rayet star and fully consistent with the fact that all GRB-SNe, so far observed, belong to Ic types, i.e., they derive from the collapse of H/He stripped-off massive stars.

iii) Only $0.4\% - 3\%$ of SNe-Ibc (corresponding to less than 1% of all core-collapse SNe) are capable to produce GRBs. Therefore some special circumstances are requested to allow a massive star to become a GRB progenitor. Recent theoretical studies indicate that rotation (Woosley & Hegel 2006; Yoon & Langer 2005), metallicity (Fruchter et al. 2006), binarity (Podsiadlowski et al. 2004, Mirabel 2004) may play an important role (see also Campana et al. 2008).

iv) Recent observations of GRB 060614 (Della Valle et al. 2006b, Fynbo et al. 2006, Gal-Yam et al. 2006) challenge the idea that all long-duration GRBs are produced in bright Supernova explosions. Any SN associated with this GRB was at least 200 times fainter than the other GRB-SNe. This fact may suggest that GRB 060614 was produced by a ”fall-back’ mechanism, which depleted the SN ejecta of most ^{56}Ni mass, resulting in a so called “dark” hypernova (see Nomoto et al. 2007).

v) SN 2008D associated with the very faint XRF 080109 exhibited several novel features with respect to other GRB-SNe: a) an early, narrow optical peak, b) disappearance of the broad lines typical of SN Ic HNe, c) development of He lines as in SNe Ib. The theoretical modeling has shown that SN 2008D derived from a $\sim 30 M_{\odot}$ star and its explosion energy (E$\approx 6 \cdot 10^{51}$ erg) and ejected mass ($\sim 7 M_{\odot}$) are intermediate between normal SNe Ibc and HNe. When it collapsed a black hole formed and weak, mildly relativistic jets were launched, which caused the XRF. SN 2008D is probably among the weakest explosions that produce relativistic jets and it should represent the link between “normal”core-collapse Supernovae and GRBs/Hypernovae.

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