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SUPERNOVAE AND GAMMA RAY BURSTS

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RESUMEN

Se revisa el estatus observacional de la conexión Supernova (SN)/Estallido de Rayos-Gamma (GRB). Recientes (y no tan recientes) observaciones de GRBs largos sugieren que una fracción significativa de ellos (pero no todos) están asociados con supernovas brillantes del tipo Ib/c. Estimaciones actuales de las tasas de producción de GRBs y SNs dan una razón para GRB/SNe-Ibc en el rango $\sim 0.4\% - 3\%$. Un análisis de la asociación GRB 060218/SN 2006aj encuentra que la SN y el GRB coinciden temporalmente dentro de ~ 0.1 días. Las observaciones recientes del GRB 060614 apuntan a la existencia de una nueva clase de GRB de larga duración que no está acompañada de una supernova brillante.

ABSTRACT

We review the observational status of the Supernova/Gamma-Ray Burst connection. Recent (and less recent) observations of long duration Gamma-ray bursts suggest that a significant fraction of them (but not all) are associated with bright SNe of type Ib/c. Current estimates of the SN and GRB rates yield a ratio GRB/SNe-Ibc in the range $\sim 0.4\% - 3\%$. An analysis of the association GRB 060218/SN 2006aj finds that the SN and the GRB are coeval events within ~ 0.1 days. Recent observations of GRB 060614 point out the existence of a new class of long-duration Gamma-ray Burst not accompanied by a bright supernova.

Key Words: **GAMMA-RAYS: BURSTS — STARS: SUPERNOVAE**

1. INTRODUCTION

Observations of Gamma-ray Bursts (GRBs) from space and ground-based telescopes have firmly established the existence of a link between long-duration GRBs and the death of massive stars. This conclusion is based on three observational milestones: i) the discovery of four clear cases of association between "broad lined" supernovae (i.e. SNe-Ib/c characterized by a large kinetic energy, often labeled as hypernovae, HNe hereafter) and GRBs, namely 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) long GRBs are located inside star forming galaxies (Djorgovski et al. 1998; Fruchter et al. 2006). The commonly accepted theoretical scenario (e.g., Woosley & Bloom 2006) suggests 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 $\sim 20 M_\odot$ and a bright SNe-Ibc is the final product. If on the one side, observations of GRB 060218 give support to this scenario (Campana et al. 2006), on the other one, very recent observations of GRB 060614 (Della Valle et al. 2006b; Fynbo et al. 2006; Gal-Yam et al. 2006) have shown that long-duration GRBs without an accompanying (bright) SN do exist.

2. SN/GRB ASSOCIATIONS IN THE LOCAL UNIVERSE

2.1. *GRB 980425 and SN 1998bw*

SN 1998bw was the first SN found to be associated with a GRB. GRB 980425 was discovered in the nearby galaxy ESO 184-G82 at $d = 40 Mpc$ and it was underenegetic by 4 orders of magnitudes with respect to typical "cosmological" γ–budget of about 10^{51} erg. Also the evolution of SN 1998bw was peculiar (Patat et al. 2001). It was very bright at maximum ($M_V \sim -19$), the ejecta exhibited unusual high expansion velocities (about 30,000 km/s) and the radio emitting region associated with the GRB-SN was expanding at mildly relativistic velocities ($\Gamma \sim 2$, Kulkarni et al. 1998).

The theoretical modeling of the light curve and spectra suggests that SN 1998bw can be well reproduced by the explosion of an H-envelope stripped

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star, of about $40M_\odot$ on the main sequence (e.g., Woosley et al. 1999; Nakamura et al. 2001). This picture is consistent with the radio properties of SN 1998bw, which can be explained as due to the interaction of a mildly relativistic shock with the dense circumstellar medium (Tan et al. 2001; Weiler et al. 2002) due to the massive progenitor wind. Maeda et al. (2006) have recently modeled the bolometric lightcurve of SN 1998bw with a smaller amount of ^{56}Ni ($\sim 0.4\ M_\odot$) by assuming that the SN explosion was highly asymmetric (see also Höflich, Wheeler, & Wang 1999).

2.2. *GRB 030329/SN 2003dh*

GRB 030329 was discovered by the HETE–2 satellite at a redshift $z = 0.1685$ (Greiner et al. 2003). SN features were detected in the spectra of the afterglow by several groups (Stanek et al. 2003; Hjorth et al. 2003; Kawabata et al. 2003; Matheson et al. 2003) about one week later. The associated SN (2003dh) looked similar to SN 1998bw. Both the gamma-ray energy budget and afterglow properties of this GRB were similar to those observed in other GRBs, and therefore, the link between GRBs and SNe was finally established to be more general. The modeling of the early spectra of SN 2003dh (Mazzali et al. 2003) has shown that SN 2003dh had a high explosion kinetic energy, $\sim 4 \times 10^{52}$ erg (if spherical symmetry is assumed). However, the light curve derived from fitting the spectra suggests that SN 2003dh was not as bright as SN 1998bw, ejecting only $\sim 0.3\ M_\odot$ of ^{56}Ni. The progenitor was a massive envelope-stripped star of $\sim 35 - 40\ M_\odot$ on the main sequence.

2.3. *GRB 031203/SN 2003lw*

GRB 031203 was a 30s burst detected by INTEGRAL (Mereghetti et al. 2003) at $z = 0.1055$ (Prochaska et al. 2004). The burst energy was extremely low, of the order of 10^{49} erg, well below the "standard" $\sim 10^{51}$ erg of normal GRBs (Frail et al. 2001; Panaitescu & Kumar 2001) and similar to GRB 980425. However in this case, a very faint NIR afterglow could be discovered (Malesani et al. 2004). 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 on 2003 Dec 20 and Dec 30 (14 and 23 rest-frame days after the GRB) are remarkably similar to those of SN 1998bw obtained at comparable epochs (Malesani et al. 2004). The light curve of SN 2003lw is also similar to that SN 1998bw, though characterized by a slower temporal evolution (about $\sim 10\%$). If the assumption on the reddening is correct, SN 2003lw appears to be brighter than SN 1998bw by 0.3 mag in the V, R, and I bands. The absolute magnitudes of SN 2003lw are hence $M_V = -19.3 \pm 0.15$, $M_R = -19.5 \pm 0.1$, and $M_I = -19.5 \pm 0.1$. An analysis of its photometric and spectroscopic evolution (Mazzali et al. 2006) indicates that this Hypernova had a main sequence mass of 40-50 $M_\odot$ and produced a large amount of Ni, possibly $\sim 0.5 - 0.6\ M_\odot$.

2.4. *GRB 060218/SN 2006aj*

GRB 060218 was detected by Swift (Gehrels et al. 2006) 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 (see Figure 2 in Campana et al. 2006). 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 high energy spectrum soften with time and can be fitted with a power-law, as observed in other GRBs. 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 black body component shows a decreasing temperature accompanied by an increasing luminosity, which implies an increase in the apparent emission radius from an initial 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 (see Patat et al. 2001). After assuming linear expansion one can estimate the star radius of the progenitors to be of the order of 5×10^{11} cm. This 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 (produced after the collapse of the core) emerging from the region within which the stellar wind of the massive progenitor is optically thick (about 10^{13} cm). This interpretation has been recently questioned by some authors (Li 2006; Ghisellini et al. 2006).

3. SN/GRB ASSOCIATIONS IN THE DISTANT UNIVERSE

3.1. *SN 2002lt/GRB 021211*

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

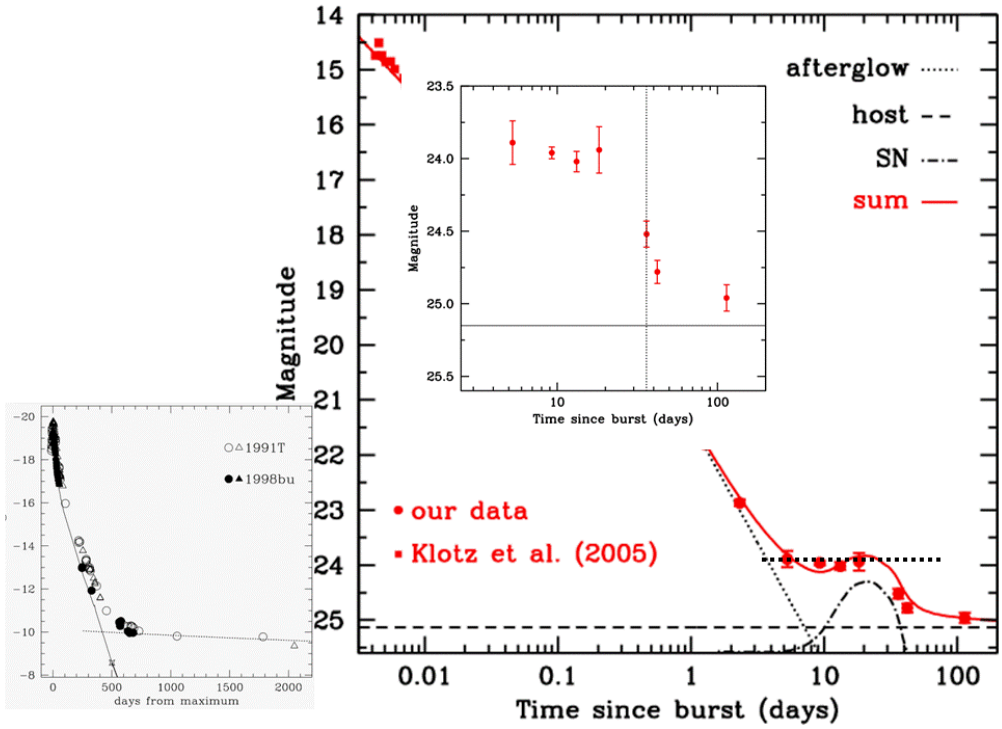

Fig. 1. Optical afterglow of GRB 050525A. In the inset (left) we show the lightcurves of the light echoes observed in SN 1991T (Schmidt94) and SN 1998bu (Cappellaro et al. 2001).

ESO VLT–UT4, together with HST observations, show a rebrightening, starting $\sim$ 15 days after the burst and reaching the maximum ($R \sim 24.5$) during the first week of January. For comparison, the host galaxy has a magnitude $R = 25.22 \pm 0.10$, as measured in late-time images. A spectrum of the afterglow + host obtained with FORS 2, 27 days after the GRB, during the rebrightening phase showed broad low-amplitude undulations blueward and redward of a broad absorption, the minimum of which was measured at $\sim$ 3770 Å (in the rest frame of the GRB), whereas its blue wing extends up to $\sim$ 3650 Å. 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. The blueshift corresponding to the minimum of the absorption implies an expansion velocity of $v \sim 14\,000$ km/s, which is often observed in SN explosions.

3.2. *GRB 050525A*

The long-duration GRB 050525A was discovered by the *Swift* satellite (Gehrels et al. 2004) on 2005 May 25.002 UT. It was a bright event, with fluence $\mathcal{F} = (2.01 \pm 0.05) \times 10^{-5}$ erg cm^{-2} and duration $T_{90} = 8.8 \pm 0.5$ s (this is the time during which 90% of the photons are collected). Spectroscopic observation of the afterglow allowed to measure $z = 0.606$. Photometric data (Figure 1) 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 during this phase is $\sim 40\%$, as estimated from our late-epoch images which show the host magnitude is fainter than $R \sim 25$. 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. A spectrum, obtained at the ESO VLT-UT1 with the FORS 2 instrument on 2005 Jun 28 (36 d after the burst, observer frame) bears some similarities with the spectrum of SN 1998bw obtained 5d past maximum and dimmed by ≈ 0.9 mag.

A more exotic interpretation of the observed flattening, calls for the effect of a light-echo. Indeed, sudden flattenings have been observed in the light curves of SNe due to the occurrence of light-echo components (e.g., Schmidt et al. 1994; Cappellaro et al. 2001; Quinn et al. 2006) during the late SN decline (see Figure 1). The light-echoes so far observed occur (several) hundreds days after the SN explosions at considerably fainter level of luminosity (about 3-4 orders of magnitudes dimmed). However if we rescale the SN parameters (e.g. Patat 2005) to the GRB phenomenon, we obtain that the light-echo component may emerge at about $\lesssim 10^d$ after the GRB event, and this has been actually observed in GRB 050525A. One would expect to reveal the presence of a light-echo by observing, in the spectrum obtained during the flattenings, the signatures of the very early optical afterglow. Although the spectrum of the afterglow of GRB 050525A is suggestive of the presence of a SN component, given the low S/N ratio of the spectrum, a light-echo contribute is not completely ruled out.

4. RATES OF SNE IB/C, HYPERNOVAE AND GRBS

A rate of $\sim 2{\times}10^4$ SNe-Ibc Gpc^{-3} yr^{-1} is derived by 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) measured in Sbc–Irr galaxies. This value of the SN rate has to be compared with the rate of "cosmological" GRBs of $\sim$ 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 $\sim 10°$–$4°$ respectively). Taking these figures at their face value, we find the ratio GRB/SNe to be in the range: $\sim 0.4\% - 3\%$. Radio surveys give independent and consistent constraints: Berger et al. (2003) find that the incidence of SN 1998bw-like events, in the nearby universe, is $< 3\%$, while Soderberg et al. (2006a) find GRB/SNe-Ibc $< 10\%$.

Several authors (e.g., Della Valle et al. 2005; Pian et al. 2006; Soderberg et al. 2006a; Cobb et al. 2006; Amati et al. 2007) have pointed out that, since the volume sampled by sub-energetic GRBs is $\sim 10^6$ times smaller than that probed by classical, distant GRBs, the frequency of occurrence of sub–energetic GRBs may be dramatically higher, by $\gtrsim 2$ orders of magnitude, than the rate of "cosmological" GRBs. However, Guetta & Della Valle (2007) have found that sub-energetic GRBs are, on average, much less collimated events than "cosmological" GRBs ($f_b^{-1} \lesssim 10$, see also Soderberg et al. 2006b), therefore the discrepancy between the intrinsic rates of the two types of GRBs may be considerably smaller, likely of the order of a factor of $\gtrsim 3$. So, given the uncertainties, we cannot exclude that one single population of GRBs, responsible for producing both the sub-energetic/isotropic and highly beamed components, is at play.

5. LONG DURATION GRBS WITHOUT (BRIGHT) SUPERNOVA

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 SN explosions. Indeed any "potential" SN associated with this GRB was at least 100 times fainter (in R band) than the other SNe associated with GRBs (see Figure 2). This fact may suggest that GRB 060614 is the proto-type of a new class of long-duration GRB which are produced in a new kind of massive star death, different from those producing bright SNe-Ibc. One possible explanation for this behavior is 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 broad-lined SNe-Ibc associated with GRBs, but it falls back and it is swallowed by the newborn black-hole. If this mechanism is at play, a consequence is that only the tiny fraction of *Ni* in the jets can escape from the exploding progenitor. This fact implies that less than $\sim 10^{-4} M_\odot$ of *Ni* are ejected and a so small amount can explain the very low luminosity ($M_B \lesssim -13$) of the (possible) SN associated with GRB 060614.

Present data are also consistent with different scenarios where the SN has occurred months of years before the GRB (Vietri & Stella 1999), or merging mechanisms (e.g., Eichler et al. 1989), similar to those called for explaining "short" GRBs, as an analysis of the temporal lags of the high energy spectral features might suggest (Gherels et al. 2006, but see Amati et al. 2007 for a different view).

6. CONCLUSIONS

A decade of GRB observations have produced an amazing advance in our understanding of the GRB-SN phenomenon and a number of firm conclusions may be drawn:

i) A significant fraction of long duration GRBs originates from the death of massive stars. This fact is well documented by: a) the direct observations of four SNe associated with GRBs; ii) the theoretical modeling of their spectra and lightcurve which suggest progenitor stars more massive (on the main sequence) than $\sim 20 M_\odot$; b) a dozen of rebrightenings, detected during the late stages of the afterglows, are well reproduced by adding SN components to the afterglow lightcurves. In 3 cases SN features have been

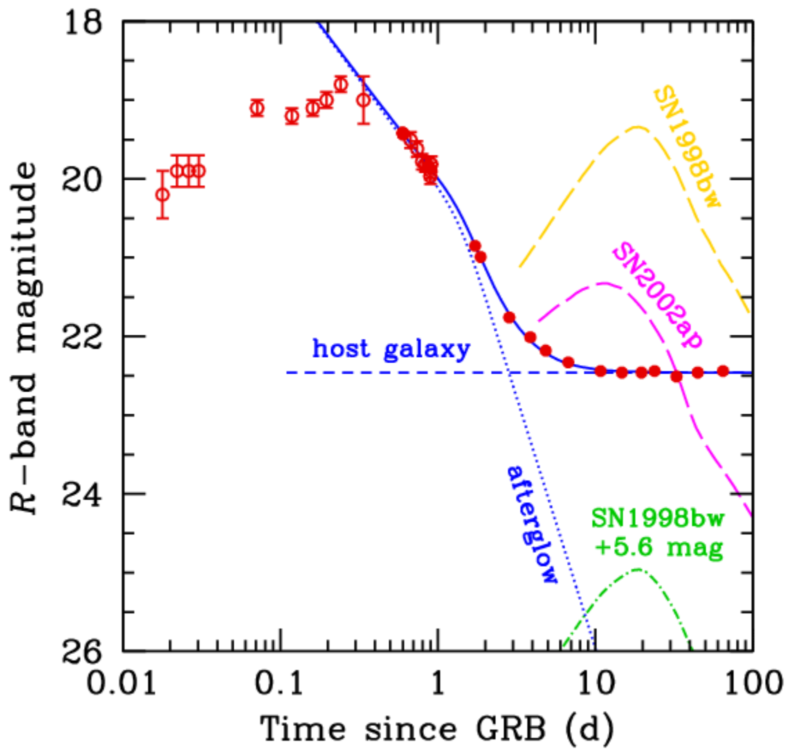

Fig. 2. Light curve of the optical emission from GRB 060614. The circles represent the observed data. There is no sign of rebrightening due to a supernova. The light curve after 0.3 day (blue solid line) has been decomposed in the sum of two components: the afterglow (blue dotted line) and the host galaxy (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 Figure 2 of Della Valle et al. 2006b).

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 Ib/c types, i.e., they derive from the collapse of H/He stripped-off massive stars.

iii) The near simultaneous observations of the non thermal (GRB) and thermal (SN) emissions in the GRB 060218/SN 2006aj association, indicate that the SN and the GRB are coeval events within ~ 0.1 day. This is a result with important theoretical implications. Before the occurrence of GRB 060218 the simultaneity between GRB and SN events was verified within a few days (see Della Valle 2006).

iv) 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.

v) 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. Indeed any SN associated with this GRB was at least 100 times fainter (in R band) than the other GRB-SNe. This fact may suggest that GRB 060614 is the prototype of a new class of long-duration GRB which are produced in a new kind of massive star death, different from those producing bright SNe-Ibc.

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