The supernova–gamma-ray burst–jet connection

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The observed association between supernovae and gamma-ray bursts represents a cornerstone in our understanding of the nature of gamma-ray bursts. The collapsar model provides a theoretical framework for this connection. A key element is the launch of a bipolar jet (seen as a gamma-ray burst). The resulting hot cocoon disrupts the star, whereas the $^{56}$Ni produced gives rise to radioactive heating of the ejecta, seen as a supernova. In this discussion paper, I summarize the observational status of the supernova–gamma-ray burst connection in the context of the ‘engine’ picture of jet-driven supernovae and highlight SN 2012bz/GRB 120422A—with its luminous supernova but intermediate high-energy luminosity—as a possible transition object between low-luminosity and jet gamma-ray bursts. The jet channel for supernova explosions may provide new insights into supernova explosions in general.

1. Introduction

SN 1998bw [1,2], coincident in space and time with GRB 980425, remains the prototype radio-bright, broad-lined (BL) type Ic supernova, against which other supernova–gamma-ray bursts are measured up. GRB 980425, however, was peculiar, with an isotropic equivalent energy release in gamma rays of only $E_{\gamma,\text{iso}} \sim 10^{48}$ erg. The optical lightcurve of SN 1998bw, depicted in figure 1, exhibited a characteristic rise to peak of about $M_V = -19.2$ mag in about 16 days, similar to a Ia supernova. MacFadyen & Woosley [5, p. 288] predicted that ‘all gamma-ray bursts produced by the collapsar model will also make supernovae like SN 1998bw’. In this model, the progenitor star is a Wolf–Rayet star [6,7], i.e. a massive star that has shed its envelope of hydrogen and helium, possibly through eruptions [8].
The ultimate proof of a SN 1998bw-like supernova associated with a ‘normal’ cosmological gamma-ray burst with $E_{\gamma, \text{iso}} \sim 10^{52}$ erg came with the spectroscopic identification of SN 2003dh associated with GRB 030329, as a supernova spatially and temporally coincident with the gamma-ray burst, and with lightcurve properties and spectroscopic broad-line evolution very similar to that of SN 1998bw [9,10].

The night before the Royal Society Discussion Meeting on ‘New windows on transients across the Universe’, GRB 120422A was observed by Swift and subsequently by ground-based telescopes at a redshift of 0.28. An accompanying supernova was predicted at the meeting and indeed reported soon after as SN 2012bz [11,12].

In this paper, I focus on ‘jet-driven’ supernovae and their relation (or lack thereof) to the different classes of gamma-ray bursts and highlight the importance of SN 2012bz/GRB 120422A. More comprehensive (and less speculative) reviews of the supernova–gamma-ray burst connection can be found in Woosley & Bloom [13] and Hjorth & Bloom [3].

2. Supernovae associated with long-duration gamma-ray bursts

There seem to be two types of long-duration gamma-ray bursts. The exact division is unclear but we will discuss them, in turn, in the following sections.

(a) Low-luminosity gamma-ray bursts

Low-luminosity gamma-ray bursts (also termed ‘sub-energetic’ or ‘nearby’ bursts) seem to be about 100 times as common as the other class discussed below [14], but because of their low
Figure 2. Schematic diagram illustrating the challenges in detecting supernova light on the background of the gamma-ray burst afterglow and the host galaxy. The supernova region (olive) reflects the range in lightcurves shown in figure 1. The afterglow is assumed to decay as $t^{-1.5}$; the afterglow region reflects the range in afterglow brightness reported by Kann et al. [19]. The range in host galaxy magnitudes reflect those detected in the TOUGH survey [20]. The diagram shows that observed lightcurves may either be supernova, afterglow or host galaxy dominated. All situations are encountered in nature. (Online version in colour.)

luminosities they are primarily found at low redshifts as rare events (one every approx. 3 years). They typically have single-peak high-energy prompt lightcurves, soft high-energy spectra and are often found to be X-ray flashes, i.e. gamma-ray bursts with peak energies below approximately 50 keV. Observational evidence suggests that the radio and high-energy emission is due to the breakout of a relativistic shock from the surrounding massive wind of the progenitor star [2,15–18]. Apart from SN 2003dh (and possibly SN 2012bz), the best-studied supernovae related to gamma-ray bursts are all members of this class. Their lightcurves are shown in figure 1.

(b) Jet gamma-ray bursts

These are also known as ‘normal’ or ‘cosmological’ gamma-ray bursts (or ‘collapsar’ bursts, although this is a somewhat theory-laden term) and are characterized by more complex prompt emission lightcurves and higher energies, luminosities and peak energies. They are believed to arise from emission from a relativistic jet at large distances from the progenitor star.

Observing a supernova related to a gamma-ray burst at higher redshift is challenging because of possible contamination by the host galaxy (which often appears unresolved in ground-based observations) and the afterglow. This is illustrated in figure 2. Indeed, as shown by Lipkin et al. [21], the lightcurve of GRB 0303029 did not exhibit a conspicuous lightcurve bump from SN 2003dh because it was afterglow dominated. Besides 2003dh (shown in figure 1), the best example of a supernova related to a gamma-ray burst in this class is SN 2010ma [22] (and possibly SN 2012bz).

(c) Statistical properties of supernovae associated with gamma-ray bursts

Inferring statistical properties of supernovae associated with gamma-ray bursts requires a well-defined sample. For this purpose, Hjorth & Bloom [3] devised a grading scheme for each supernova claimed in the literature to be related to a gamma-ray burst. The evidence for a supernova was graded A–E.¹ Based on supernovae with grades A–C, we plot in figure 3 the

¹We have created a website (http://www.dark-cosmology.dk/GRBSN) dedicated to providing updates to the list of supernovae related to gamma-ray bursts, the grading of the observational evidence for a supernova, and supplementary information on the supernovae and the associated gamma-ray bursts.
Figure 3. Supernova optical peak brightness versus gamma-ray burst (GRB) isotropic luminosity [23,24] for grade A–C systems [3]. Low-luminosity gamma-ray burst supernovae ($E_{\gamma,\text{iso}} < 10^{48.5} \text{ erg}$, olive) and supernovae from jet gamma-ray bursts ($E_{\gamma,\text{iso}} > 10^{49.5} \text{ erg}$, orchid) have similar distributions of peak brightness. SN 2012bz/GRB 120422A is highlighted (orange) as a possible transition object in the grey area: $10^{48.5} \text{ erg} < E_{\gamma,\text{iso}} < 10^{49.5} \text{ erg}$ [25]. (Online version in colour.)

distribution of peak supernova magnitudes as a function of isotropic equivalent luminosity in gamma rays. Defining $L_{\gamma,\text{iso}} = E_{\gamma,\text{iso}} T_{90}^{-1} (1 + z)$, we have tentatively identified low-luminosity gamma-ray bursts as having $L_{\gamma,\text{iso}} < 10^{48.5} \text{ erg s}^{-1}$ and jet gamma-ray bursts as having $L_{\gamma,\text{iso}} > 10^{49.5} \text{ erg s}^{-1}$. There is a real dispersion in the peak magnitudes; supernovae related to gamma-ray bursts are evidently not standard candles. It remains an open question whether they are standardizable similar to type Ia supernovae [4,26]. It is evident that the lightcurves of the subsample of supernovae shown in figure 1 exhibit a clear correlation between the peak magnitude and the width of the peak.

We note that beaming and viewing angle can significantly affect the inferred high-energy luminosity [27]. For example, GRB 091127, which appears in the high-luminosity (jet) part of figure 3, has been suggested to be a sub-energetic burst [28] owing to a beaming correction. Nevertheless, it is evident that there appears to be a parabola-shaped upper envelope to the brightness of supernovae as a function of high-energy luminosity. By the time of the meeting, there were no gamma-ray bursts with convincing supernovae in the range $10^{48.5} \text{ erg} < E_{\gamma,\text{iso}} < 10^{49.5} \text{ erg}$. This changed with SN 2012bz/GRB 120422A, which fills this gap in high-energy luminosity as one of the brightest supernovae associated with a gamma-ray burst ever detected [29].

How do these peak magnitudes compare with other similar supernovae, i.e. type Ic supernovae, with no hydrogen or helium in their spectra? Using the well-defined sample of normal Ic supernovae from Drout et al. [30] and a more heterogeneous sample of BL Ic supernovae from a variety of sources, we plot cumulative histograms of their peak magnitudes in figure 4. Type Ic supernovae seem to be fainter than supernovae related to gamma-ray bursts, whereas the situation is less clear-cut for Ic-BL supernovae with no gamma-ray bursts. We note that strong observational evidence (grade A–C) quite naturally will bias our sample against fainter supernovae.

A comparison with Ic-BL is interesting because the rates of low-luminosity gamma-ray bursts and Ic-BL are comparable, suggesting perhaps a common origin and indicates that low-luminosity gamma-ray bursts, as expected, may not be strongly beamed [31].
Figure 4. Cumulative distributions of the brightness of different kinds of Ic supernovae. The supernovae associated with gamma-ray bursts graded A, B or C are from Hjorth & Bloom [3]. The normal Ic supernovae are from Drout et al. [30]. The Ic-BL distribution comes from a variety of sources and as such represents a more ill-defined sample. The gamma-ray burst supernovae generally appear brighter than normal Ic supernovae, although it should be noted that they are likely biased against faint systems. The brightness distribution of Ic-BL is probably consistent with that of gamma-ray burst supernovae although there may be a lack of very bright gamma-ray burst supernovae. (Online version in colour.)

3. Supernova-less gamma-ray bursts

Two classes of gamma-ray bursts are not accompanied by bright supernovae.

(a) Short gamma-ray bursts

Short-duration, hard-spectrum gamma-ray bursts [32], with durations $T_{90} < 2 \text{ s}$, are known not to lead to supernovae. In figure 1, we have plotted the upper limits on the existence of supernovae accompanying GRB 050509B [33] and GRB 050709 [34]. These constrain any supernova to be about 100 times fainter than SN 1998bw at peak. This is consistent with short gamma-ray bursts being the results of compact object mergers.

The data also rule out the existence of an early rebrightening in GRB 050509B [33] at 1.5 days in the restframe. Bright transient emission, dubbed a ‘mini SN’ [35,36], ‘kilonova’ [37] or ‘macronova’ [38], is expected to peak around the optical–UV range within a day or so with a semi-thermal spectrum [35]. GRB 050509B sets very strong constraints on such emission [33,39,40].

(b) Long supernova-less gamma-ray bursts

Perhaps surprisingly, some long-duration gamma-ray bursts are not accompanied by bright supernovae. As shown in figure 1, the constraints on GRB 060505 and GRB 060614 are about as constraining as the those related to the short gamma-ray bursts discussed earlier. These puzzling systems may be related to non-$^{56}$Ni-producing supernovae or they may be merger gamma-ray bursts with longer durations than usually found [41–45].

(c) Mind the gap

It is quite remarkable that current observations reveal a clear gap between the brightnesses of gamma-ray burst supernovae, at around absolute magnitude $-17$ to $-19$, and the upper limits on long supernova-less gamma-ray bursts at around $-12$ to $-14$ mag. Finding faint supernovae is of course difficult and fainter supernovae will likely be detected but the current factor of 100 may indicate that there is not a simple continuum of events.
Table 1. The supernova–gamma-ray burst–jet connection.

<table>
<thead>
<tr>
<th>core-collapse supernovae</th>
<th>supernova–gamma-ray bursts</th>
<th>gamma-ray bursts</th>
</tr>
</thead>
<tbody>
<tr>
<td>relativistic Ic-BL (SN 2009bb)</td>
<td>low-luminosity GRBs (SN 1998bw–GRB 980425)</td>
<td>fall-back supernovae? (GRB 060505)</td>
</tr>
<tr>
<td>type IIn? (SN 2010jp)</td>
<td>jet GRBs (SN 2003dh–GRB 030329)</td>
<td>mergers (GRB 050509B)</td>
</tr>
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</table>

4. Engine-driven supernovae

The collapsar model [5] operates with two time scales, the duration of the active ‘engine’ (jet), $t_E$, and the time for shock breakout, $t_S$. A successful gamma-ray burst requires the engine to be active for longer than the shock-breakout time. Bromberg et al. [46] and Lazzati et al. [47] have used this picture to explore the consequences of the relative durations for the resulting supernovae and gamma-ray bursts (an alternative jet scenario is presented by Papish & Soker [48]):

- $t_E > t_S$: a normal jet gamma-ray burst accompanied by a Ic-BL is produced;
- $t_E \approx t_S$: a low-luminosity gamma-ray burst accompanied by a Ic-BL or a relativistic Ic-BL with no gamma-ray burst is produced; and
- $t_E < t_S$: a non-relativistic supernova but no gamma-ray burst is produced.

In this picture, relativistic supernovae, such as SN 2009bb [49,50], are jet-driven supernovae, similar to low-luminosity gamma-ray bursts. It is worth noting that a low luminosity is not necessarily synonymous with a short engine duration, i.e. it may be possible to have low-luminosity jet gamma-ray bursts, such as possibly GRB 120422A.

In the collapsar model, one could also imagine that the engine does not occur in a stripped-envelope core-supernova but in a type II supernova with a hydrogen and/or helium layer that would prevent the escape of the jet (see also [51]). Such massive stars may have a dense circumstellar medium that would make them appear as type IIn supernovae, as suggested by, for example, Nomoto et al. [52] and Chevalier [53]. Recently, a possible jet-powered IIn (SN 2010jp) was reported [54], albeit not a relativistic one.

The picture regarding jet-driven supernovae and gamma-ray bursts that emerges from the discussion in this paper is summarized in table 1. SN 2012bz/GRB 120422A, which may be a transition object between the low-luminosity and jet gamma-ray bursts, reminds us that this fairly simple picture could easily be more complex.

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References


