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The supernovae associated with gamma-ray bursts

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The connection between long GRBs and supernovae is now well established. I briefly review the evidence in favor of this connection and summarise where we are observationally. I also use a few events to exemplify what should be done and what type of data are needed. I also look at what we can learn from looking at SNe not associated with GRBs and see how GRBs fit into the broad picture of stellar explosions.

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1. Introduction

The connection between gamma-ray bursts (GRBs) and supernovae (SNe) has existed for longer than the "official" history of GRBs. Colgate [8] predicted that exploding stars should emit γ rays. Even though it turned out that this model for GRB prompt emission is not correct, it meant that a connection between SNe and GRBs was on everybody's mind from the beginning. Indeed, Klebesadel, Strong & Olson [21] searched for spatial and temporal coincidence between explosive events (novae and supernovae) and GRBs. Although they didn't find any coinciding event, this was not enough to discourage further similar searches. It is only in the afterglow era that major progress could finally be made and that a clear link between long GRBs and SNe would be firmly established.

This review is not an attempt to be exhaustive so there is no discussion of all known or candidate SNe associated with GRB. I will rather try to show where we are now as a community and to place these SNe in a general context. Several recent reviews took a close look at the evidence for each SN/GRB and should be consulted for specific information about any particular object (see e.g. [42, 17]).

2. From suspicion to proof

GRB980425 was quickly associated with a supernova, SN 1998bw. The spectra of the SN clearly showed that it was a type Ic – meaning that the spectrum showed no sign of hydrogen nor helium. The association between the GRB and the SN meant that the burst was extremely faint however ($E_{iso} < 10^{48}$ erg). SN 1998bw itself was also peculiar, as it was a very bright SN, showed very broad lines (BL) and had a large expansion velocity (e.g. [12]. Because of this highly unusual nature – very weak and very nearby while the SN was very bright, there was still a question mark over this event and some fraction of the community was still waiting for a GRB at a genuinely "cosmological" distance.

This happened with GRB030329. The burst was close enough that a SN could be seen, yet it was distant and bright enough that it could be classified as a genuine GRB. Unambiguous SN features became visible in afterglow spectra a few days after the burst ([38, 16]). The SN was shown to be very similar to SN 1998bw [26] and was also classified as a SN Ic-BL. This event removed any doubt as to the association between SNe and GRBs.

Since then, several other GRBs have had indisputable spectral evidence supporting the presence of a SN (see Table 1). Several good quality spectra (between 2 and many) have been obtained also for GRB031203 (SN 2003lw [24]), XRF060218 (SN 2006aj [33]), GRB100316D (SN 2010bh, [7, 3]), GRB120422A (SN 2012bz, [25, 34])[1] These SNe share the characteristics of SN 1998bw, in the sense that they are of type Ic and they have broad lines, indicative of high expansion velocity.

There were attempts to obtain a spectrum of the SN for a number of other GRBs but the evidence is not as solid as one would wish. The reader is referred to [17] for a detailed discussion of each event and associated evidence.

[1]This last event is still a developing story as of this writing. While the presence of a SN is clear, the SN itself is not yet fully characterised.

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a) GRBs with highest quality spectroscopic evidence:
GRB980425 ≡ SN 1998bw, GRB030329 ≡ SN 2003dh, GRB031203 ≡ SN 2003lw, GRB060218 ≡ SN 2006aj, GRB100316D ≡ SN 2010bh, GRB091127 ≡ SN 2009nz, GRB120422A ≡ SN 2012bz
b) Other GRBs with SN evidence:
GRB970228, GRB980326, GRB990712, GRB991208, GRB000911, GRB011121, GRB020305, GRB020405, GRB020410, GRB020903, GRB021211, GRB030723, GRB040624, GRB041006, GRB050416A, GRB050525A, GRB050824, GRB060729, GRB070419A, GRB080319B, GRB081007, GRB090618, GRB100418A, GRB101219B, GRB101225A

Table 1: A list of GRBs where some evidence for a SN has been found (see Table 9.1 in [17] for references related to any particular GRB). The first category includes those events with a very clear spectroscopic signature; the second category includes event where the evidence ranges from good to poor.

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2.1 Light curves bumps

Short of obtaining a spectrum around the time of the SN peak luminosity, a well-sampled light curve in several filters can also show evidence for a SN. This will take the form of a "slowing 'down" of the light curve or even a rebrightening. A fairly large number of bursts have displayed such a behaviour and in most cases, the bump can be reasonably well fit with a SN light curve (see Table 1). These SNe are represented as "modified SN 1998bw", in the sense that the adopted model light curve is usually that of SN 1998bw, stretched or compressed in time and shifted in brightness (and properly accounting for the different luminosity distance and *k*-correction).

The brightness of these bumps is usually within a factor of a few of SN 1998bw (e.g. [43, 10, 5]) albeit slightly fainter on average, which is not surprising given that SN 1998bw was a very bright event. At this point, one can say that in nearly every case where we should have been able to see a bump, a bump has been seen and it corresponds, in brightness and timing, to a SN.

2.2 Properties of SNe of GRBs

We want to understand the explosions so that we can ultimately constrain the progenitors of GRBs. A good multi-colour light curve, coupled with a velocity measurement at maximum light, can be modelled analytically [1] to obtain explosion parameters: kinetic energy E_k, mass of the ejecta M_{ej}, and mass of ^{56}Ni synthesised. This has been done for a few events (see [6, 31, 3] for the case of XRF100316D). This approach may be subject to systematic errors however and modelling based on light curve and time-series spectroscopy yields more robust results (e.g. [18, 27, 23]). This provides a better understanding of the ejecta's structure and yields more reliable results than simple light curve analysis because it avoids several simplifications. The results of such modelling give a range of values for each parameter: the kinetic energy is $E_k = 2 - 60 \times 10^{51}$ erg, the ejected mass ranges from 2 $M_\odot$ to 13 $M_\odot$ and the mass of ^{56}Ni synthesised in the explosion is between 0.1 $M_\odot$ and 0.7 $M_\odot$.

3. Cautionary tales

In some cases, the observational data may not allow us to detect a SN signature. One such example is GRB070419A. While there was an initial claim for a SN [15] based on a photometric bump, a full analysis of all the light curve data showed that the late time behaviour could be fully explained by a fairly shallow decay of the afterglow [28]. In order to determine the SN brightness, we need to know very well what the afterglow is doing. This means that a well-sampled GRB light curve is necessary for tens of days; not only for a few hours. Observing the source past the SN maximum is needed as well; if any "rebrightening" is seen, the fast fading of the SN will leave a different signature in the light curve than the power law decay of the afterglow.

Another example is given in Fig. 1. The left panel is a light curve displaying a more or less power law decay. From this light curve, it is impossible to tell whether there is a SN hidden in the data or not. The right panel of the figure shows the full light curve, which is for GRB030329. Now, obviously a SN was there to be found in the data. Assume for a moment that this burst had been at $z \sim 0.5$, hence much fainter, we would have had much less data, the light curve would have looked like the left panel of Fig. 1 and it would have been very hard to find a SN in the light curve. The point here is that even if we do not see an obvious SN bump, there may well be one but we need good enough data to separate the relative contributions of the afterglow and SN. The case of GRB060729 is particularly instructive: there is no SN bump to be seen simply because the afterglow was very bright but a careful analysis revealed a bright SN in the light curve [5].

Another example is provided by GRB101225. There are two "competing" interpretations regarding the nature of this event. One is a cosmological GRB ($z \simeq 0.33$) with a SN bump [39], the other is a minor planetary body tidally disrupted by a (Galactic) neutron star [4]. The point here is not to decide which interpretation is best but to emphasise again that *the right type of data at the right time* will go a long way towards removing any ambiguities in the analysis. This burst serves as a stark reminder that nothing replaces spectroscopy.

4. GRBs or SNe we do not see

The central point of this section is about negatives: not finding what we expect or finding what we do not expect.

4.1 Observing a GRB and finding no SN

There are times when, try as you may, there is no SN to be found. Two events in particular, GRB060505 and GRB060614, are now etched in the collective consciousness. Both were at a redshift low enough that a SN even substantially fainter than SN 1998bw would have been detected easily. The limits on the brightness of any SN are actually very strong: in both cases any SN would have to have been at least 100 times fainter than SN 1998bw at peak (e.g. [13, 14, 9]). Several other events also showed no sign of a SN, although in some cases the lack of redshift makes the evidence weaker ([36, 22]).

While there may still be some lingering questions regarding the nature of these bursts, they may be in a different class than most long GRBs. A possibility is that they have slightly different progenitors. Indeed, it may well be possible to make a GRB (i.e. a relativistic jet) without making

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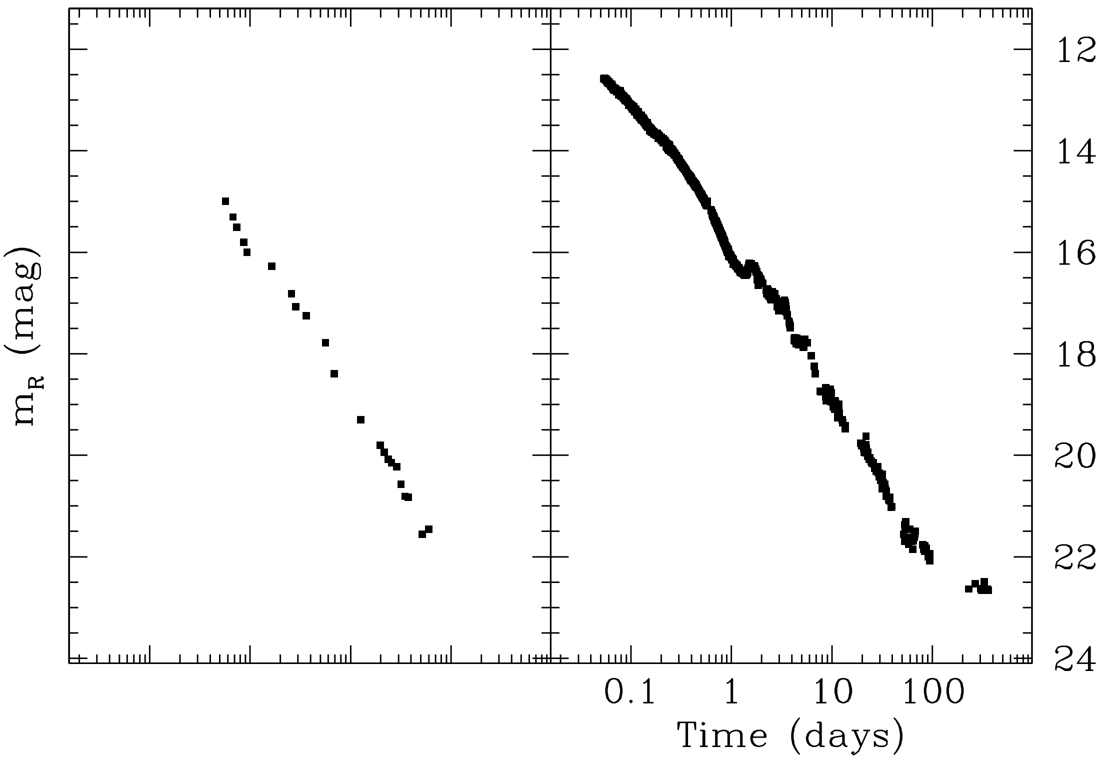

Figure 1: *Left:* An *R*-band light curve for a seemingly anonymous GRB. The afterglow decays by several magnitudes over ~ 2.5 decades in time. At first sight, there is no SN bump. *Right:* The whole *R*-band light curve of GRB030329 which is the event on the left. There is no doubt that there was a SN associated with this event.

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a bright SN (e.g. [41, 40, 30]). A bright burst of γ rays may be the only electromagnetic signature of such events. Obviously we need to find more of these "failed" SNe. This is why it is important to monitor low redshift GRBs for several weeks. The absence of a SN may tell us even more than an actual detection.

4.2 Observing a SN and serendipitously finding a GRB

Given that GRBs emit their radiation in a narrow cone, we miss most of them (i.e. those pointing away from Earth). The emission becomes visible however at late times in the radio when the afterglow is emitting essentially isotropically. Because we can separate normal SNe from late-time jet emission via their luminosities (jets are much more luminous than SNe, e.g. [37] and references therein), this offers a way of finding GRBs whose high-energy emission was directed away from us.

Observations of SNe at radio wavelengths have recently uncovered such a case. The radio luminosity of SN 2009bb places it squarely among the jet-associated SNe [37], yet no GRB was observed. Another possible case is SN 2007gr [32]. These recent observations of nearby SNe show that the number of jets found via their SN emission may be comparable to the number of

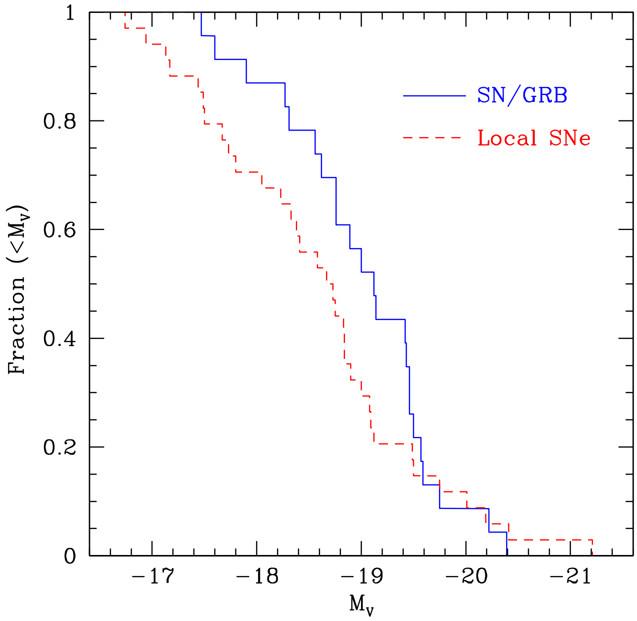

Figure 2: Cumulative distribution of peak magnitudes for local SNe Ibc (red dashed line) and the SNe associated with GRBs (blue solid line). On average, the SNe of GRBs are brighter than local SNe Ibc (based on data in [5]). This should be interpreted with some caution however as observations of a SN/GRB at an intermediate redshift (say $z \simeq 0.3-0.5$) is easier when the SN is bright.

SNe found via their early gamma-ray emission. If the two techniques have comparable yields, they should both be pursued as each complements the other.

5. The SNe of GRBs in a general context

From their relative rates, we know that GRBs represent a very small fraction of all SNe. From their observed properties however, they do stretch the parameter space of stellar explosions. We know that local "normal" SNe and GRBs mark the explosions of massive stars. What sets GRBs apart from other SNe is the large amount of energy that goes into relativistic ejecta. What we ultimately want to know is why a small fraction of SNe manage to do that while most of them do not. Comparing the respective observational properties of these two types of explosions is a fruitful way of understanding their differences.

One similarity is the spectroscopic type, Ic, which tells us that GRB progenitors are stripped-envelope stars. They also share the same "locations" on the respective host galaxies ([11, 19]): local SNe Ic and GRBs are much more concentrated on the light of their hosts than other types of SNe. The SNe of GRBs show, on average, larger ejection velocities than local SNe Ic, they have very broad lines. They also have larger energies and peak brightnesses than local SNe Ic (see Fig. 2).

The properties of GRB host galaxies are instructive as well; they are different from those of SNe Ic. GRBs are found in relatively low luminosity irregular galaxies [11]. GRB are also found in more metal-poor environments than SNe Ic (e.g. [20, 29], see also [35] however). In this context,

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it is interesting to note that local *broad-line* SNe Ic tend to prefer low metallicity environments as well ([29]).

6. Conclusion

A bump on a light curve in itself is moderately interesting; it becomes much more valuable when combined with time-series spectroscopy because this allows us to characterise the progenitor star. Photometric monitoring low-z GRB is warranted however because this is the only way to find other SN-less GRB (like GRB060614). It is important to know what fraction of bursts can be formed via this channel. This will eventually help us understand whether these objects are a separate class altogether or part of a continuum encompassing very faint and very bright SNe.

It can be frustrating to wait for nature to be so kind as to offer us a low redshift GRB where the SN can be studied in detail. Observing nearby SNe can help us tremendously to understand GRBs in general. Radio monitoring of SNe has been proved to be a good way to find relativistic ejecta in the local universe. On the other hand, ongoing optical surveys of the sky (PTF, Pan-STARRS, SkyMapper, La Silla QUEST, CRTS, etc.) already find hundreds of SNe of all types every year. This will lead to a better understanding of the evolution and explosion of massive stars that will improve our understanding of GRBs. This is like making a jigsaw puzzle with a 1000 pieces with one blank piece among them. Obviously we do not know where it fits in the global picture but once the other 999 pieces are in place, we will will know exactly where the blank one fits and, looking at the general picture, we will have a very good idea as to what this piece should look like.

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