The Supernovae Associated with Gamma-Ray Bursts

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Abstract. Supernovae (SNe) were long suspected as possible progenitors of gamma-ray bursts (GRBs). The arguments relied on circumstantial evidence. Several recent GRBs, notably GRB 030329, have provided direct, spectroscopic evidence that SNe and GRBs are related. The SNe associated with GRBs are all of Type Ic, implying a compact progenitor, which has implications for GRB models. Other peculiar Type Ic SNe may help to expand understanding of the mechanisms involved.

1. Introduction

The mechanisms that produce gamma-ray bursts (GRBs) have long been among the mysteries of modern astrophysics. There have been a wide variety of models (see Mészáros 2002 for a review of the theories of GRBs). The discovery of optical afterglows opened a new window on the field (see, e.g., van Paradijs, Kouveliotou, & Wijers 2000). Early identification of the optical afterglows led to the measurement of redshifts for several GRBs (e.g., GRB 970508: Metzger et al. 1997), providing definitive evidence for their cosmological origin. Observations at other wavelengths, especially radio, have revealed many more details about the bursts (e.g., Berger et al. 2000; Frail et al. 2003). This only applies to the long-duration bursts at this point.

Models that use supernovae (SNe) to explain GRBs have been part of the discussion from the start (e.g., Colgate 1968; Woosley 1993; MacFadyen & Woosley 1999). Strong evidence for the GRB-SN association was first provided by GRB 980425: the optical afterglow was not found, but an unusual Type Ic SN was seen in the error box of the GRB (Galama et al. 1998; Patat & Piemonte 1998). Many other circumstantial arguments were made to connect GRBs with SNe. Direct evidence, where an afterglow is seen to transform into an SN, was first seen with GRB 030329 (Stanek et al. 2003; Matheson et al. 2003; Hjorth et al. 2003; Kawabata et al. 2003; Kosugi et al. 2004). Subsequently, two other cases have been identified: GRB 021211 (Della Valle et al. 2003) and GRB 031203 (Malesani et al. 2004). In this paper, I will review the evidence for the GRB-SN association and describe the nature of the SNe that are associated with GRBs.
2. The Circumstantial Case

There were many indirect pieces of evidence that showed an association between GRBs and SNe. Most of these actually related GRBs to massive stars, but, since massive stars do undergo core collapse to become SNe, the connection was implicit. On the large scale, the host galaxies of GRBs showed strong star formation, indicating that massive stars were present (e.g., Hogg & Fruchter 1999). More detailed studies found that the locations of GRBs within their host galaxies were associated with the regions that contained massive stars (e.g., Bloom, Kulkarni, & Djorgovski 2002).

Other circumstantial arguments derived from evidence related to the interaction of the GRB with its local environment. Massive stars in general have stellar winds, and the observations of the afterglows are consistent with models of interaction with these winds (e.g., Chevalier & Li 2000). A few GRB afterglows have shown strong absorption features at relatively high velocities (a few thousand km s$^{-1}$), the best case being GRB 021004. For that GRB, these features were interpreted as mass-loss shells from a Wolf-Rayet progenitor, again implying a massive star (Mirabal et al. 2003; Schaefer et al. 2003). Another claim of evidence for association with SNe came from reported detections of line features in the X-ray afterglows of some GRBs (e.g., Piro et al. 1999; Reeves et al. 2002) that would result from material synthesized in the collapse, followed by a GRB after a period of time. Recent reanalysis of all observations of X-ray afterglows, however, indicates that these earlier claims are not statistically significant (Sako, Harrison, & Rutledge 2004).

Perhaps the strongest element in the circumstantial case for the GRB-SN association was the presence of bumps in the afterglows of many GRBs. The traditional optical afterglow of a GRB decays as a power-law. Late-time deviations from this power law were consistent in their timing and brightness with an SN having exploded at the same time as the GRB (e.g., Bloom et al. 1999). Rebrightening, though, is not necessarily direct evidence of a supernova. That would require a spectroscopic detection.

3. The Early Clues

The first evidence for an SN associated with a GRB came when SN 1998bw was found in the error box of GRB 980425 (Galama et al. 1998). The SN was of Type Ic (see Filippenko 1997 for a review of SN types), but it was peculiar, with evidence for unusually high velocities (Patat et al. 2001). This event was odd in many ways. The GRB itself was relatively weak (Woosley, Eastman, & Schmidt 1999) and the radio emission from the SN was extraordinary, both in luminosity and the rapidity of its appearance (Kulkarni et al. 1998). This was clearly an object of great interest, but it was not conclusive proof that SNe and GRBs are related. It is, though, the framework upon which all further claims of GRB-SN connections are built.

A weaker case is GRB 011121 (Garnavich et al. 2003a; Bloom et al. 2002). A late-time bump in the light curve was observed from the ground and with HST. At $z = 0.36$, the supernova component would have been relatively bright. A spectrum of the GRB taken during the rebrightening does not show any obvious
features of an SN, but the color evolution derived from broad-band photometry is consistent with a supernova (designated SN 2001ke; Garnavich et al. 2003a).

4. The Definitive Case

While SN 1998bw was a strong hint of the GRB-SN association, no traditional optical afterglow was seen. Without that direct association, the link between GRBs and SNe was still in question. The ‘monster burst’ of 2003, GRB 030329 was to provide that link. The burst was unusually bright in gamma-rays, implying that it was relatively close. Spectroscopy of the afterglow soon confirmed a low redshift of 0.1685 (Greiner et al. 2003). As the afterglow faded, subtle features appeared in the normally flat power-law spectra of the afterglow. By subtracting a continuum based upon the early shape of the spectrum, this structure was revealed as the spectrum of an unusual Type Ic SN similar to SN 1998bw, designated SN 2003dh (Garnavich et al. 2003b). Within a few days, the SN became the dominant component in the spectrum (Stanek et al. 2003; Hjorth et al. 2003; Kawabata et al. 2003).

Figure 1. Spectra of SN 2003dh after the continuum of the GRB afterglow has been removed. The \( \Delta T \) value is the time since the GRB (observed frame). In all cases, SN 1998bw is the best match, day -6 for \( \Delta T = 9.7 \) days and day +6 for \( \Delta T = 25.8 \) days. Note also that between \( \Delta T = 9.7 \) days and \( \Delta T = 25.8 \) days is 13.8 rest-frame days, consistent with the evolution of SN 1998bw. The time of \( \Delta T = 0 \) days would correspond with 14 days before maximum for SN 1998bw, a reasonable rise time for a Type Ic SN. See Matheson et al. (2003) for more details.
Using the early power-law continuum spectrum as a model, one could decompose the observed spectra at later times into two separate components: GRB afterglow and SN spectrum. Using a least-squares technique, the best match for the SN among the low-redshift sample was SN 1998bw (Matheson et al. 2003). In fact, taking into account cosmological time dilation, the spectroscopic evolution of SN 2003dh almost exactly matched SN 1998bw (Figure 1). Models of these spectra are presented by Mazzali et al. (2003; see also Mazzali’s contribution in this volume).

An important point about the appearance of the SN was that the light curve did not show the bump that is supposed to be the characteristic of a rebrightening caused by the SN (see Matheson et al. 2003 and Lipkin et al. 2004 for a discussion of the light curve). Without the spectroscopic confirmation, the SN in GRB 030329 would still be a matter of contention.

Nebular-phase spectra of SN 2003dh show a spectrum similar to a typical Type Ic SN. Kosugi et al. (2004) present a spectrum at an age of ~3 months. A spectrum obtained with the Keck telescope by Filippenko, Chornock, & Foley (2004) in December of 2003 is much like a normal Type Ic SN (Bersier et al., in preparation).

5. Other Supernovae Associated with Gamma-Ray Bursts

Following the discovery of SN 2003dh, reexamination of spectra of an earlier burst yielded some evidence for a SN component. Della Valle et al. (2003) found that a spectrum of the afterglow of GRB 021211 had structure similar to an SN. In this case, though, the SN did not match SN 1998bw or any other peculiar Type Ic SN. Rather, it was most similar to SN 1994I, a relatively normal Type Ic.

A more clear example came with GRB 031203. Despite high foreground reddening, spectroscopy with the VLT revealed an SN component, designated SN 2003lw (Malesani et al. 2004). For this SN, SN 1998bw was again a good match. Of the four SNe with clear GRB associations, three show remarkably similar spectra.

6. Why is Type Ic Significant?

The classification scheme for SNe (see Filippenko 1997) is based upon spectroscopic features. The Type II SNe show hydrogen, while those of Type I do not. Type Ia SNe have a distinctive silicon feature and show an elemental pattern consistent with the theory that they arise from thermonuclear disruption of a white dwarf. The other Type I SNe (i.e., without the strong silicon absorption) are distinguished either by the presence (Ib) or absence (Ic) of helium.

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1It should be pointed out that “normal” is a fairly subjective term to be applied to Type Ic SNe. They are a very heterogeneous group, and it is not clear that one can define a truly normal Type Ic SN. See Matheson et al. (2001), and references therein, for a more complete discussion of the nature of Type Ic SNe.
A strong circumstantial case has tied Types II, Ib, and Ic to the same underlying mechanism of core collapse. A transition between Type II and something like a Ib was observed for SN 1993J (e.g., Filippenko, Matheson, & Ho 1993), strengthening this connection and providing an explanation for the subclasses. Models of the progenitor of SN 1993J postulated that a massive star in a binary had lost most of its hydrogen layer, leaving a small amount that produced the early spectrum of a Type II, and then revealing the helium layer below (see Matheson et al. 2000 for a summary and an extensive list of references).

Study of a large number of Type Ib/c SNe indicated that the SNe Ic had less massive envelopes than the SNe Ib (Matheson et al. 2001). This implied that the Ib SNe have lost their hydrogen, leaving the helium layer, while the SNe Ic have lost hydrogen and helium, leaving a carbon/oxygen core. The spectrum itself, though derived from the same underlying mechanism, can be very different depending on the amount of the envelope stripped from the star at the time of the explosion. If the GRB mechanism does entail a jet (e.g., MacFadyen, Woosley, & Heger 2001), then a smaller progenitor with a less massive envelope would make it easier for the jet to punch through the stellar atmosphere and still have the energy to produce the observed burst and afterglow.

7. Other Peculiar Type Ic SNe

In addition to SN 1998bw, there are several low-redshift peculiar Type Ic SNe. These are objects that show high expansion velocities and sometimes, but not always, large luminosity (they are occasionally referred to as “hypernovae”). Two well-studied such examples are SN 1997ef and SN 2002ap (Iwamoto et al. 1998, 2000; Foley et al. 2003). None of these other high-velocity SNe has been directly associated with a GRB. There is a wide diversity in their spectroscopic and photometric development, but only the ones like SN 1998bw have been related to GRBs. It is not yet clear if this is significant.

Even though the overall energy budget may be different for GRBs and these other peculiar Type Ic SNe, they are clearly unusual objects. The high velocities set them apart from a typical SN, with the only similar objects being the SNe associated with GRBs. To study the SN component of a GRB requires it to be at low redshift, a condition that also makes them rare. The peculiar Ic SNe, though, are relatively more common, and are bright enough to enable detailed studies with even modest telescopes. Study of these objects could be the first step to understanding the GRB mechanism.

8. Conclusions

While circumstantial arguments had linked SNe with GRBs, spectroscopic data was needed for irrefutable proof. This crucial piece of evidence arrived in the form of GRB 030329, wherein a direct transformation from GRB afterglow to peculiar Type Ic SNe was thoroughly observed. Later that same year, GRB 031203 provided a further link. These two, along with SN 1998bw, showed similar spectra. That they were Type Ic implied that the progenitor was a stripped-envelope star, lending credence to jet-based models for GRBs. Although these GRB-SNe
are rare, low-redshift examples of peculiar Type Ic SNe are not, providing a laboratory to understand stellar explosions in extreme circumstances.

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