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Evidence for Asphericity in Hypernova Explosions

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Abstract. The available observational data on the GRB-connected, energetic Type Ic Supernovae (Hypernovae) are reviewed and analysed, with particular emphasis on the indications that the explosions are aspherical, providing a natural link between Hypernovae and Gamma Ray Bursts.

Key words. Supernovae – Gamma-Ray Bursts – Stellar Evolution

1. Introduction

One of the most exciting developments in recent supernova (SN) studies is the discovery of very energetic SNe (Hypernovae), whose (isotropic) kinetic energy (KE) exceeds 10^{52} erg, about 10 times the KE of normal core-collapse SNe (hereafter $E_{51} = E/10^{51}$ erg), and their association with Gamma-Ray Bursts (GRBs).

The cases for a connection between SNe and GRB's are SN 1998bw/GRB980425 (Galama et al. 1998; Iwamoto et al. 1998), SN 2003dh/GRB030329 (Stanek et al. 2003; Hjorth et al. 2003; Kawabata et al. 2003), and SN 2002lt/GRB021211 (Della Valle et al. 2003) on the basis of their optical spectra. Recently, another case has been observed, SN 2003lw/GRB031203 (Thomsen et al. 2004; Gal-Yam et al. 2004; Malesani et al. 2004).

Fitting ($\lesssim$ 50 day) optical light curves and spectra of supernovae, the explosion KE and the main-sequence mass M_{ms} of the progenitor star can be derived. At least SNe 1998bw and 2003dh are classified as hypernovae (Iwamoto et al. 1998; Mazzali et al. 2003). Other possible SNe in GRBs have been reported, but in these cases the evidence was limited to the detection of 'bumps' in GRB afterglows (e.g., Bloom et al. (2002); Garnavich et al. (2003)).

The link to GRBs is a strong hint that hypernovae could be significantly aspherical, as is widely believed for GRBs (e.g., Frail et al. (2001)). This speculation received further support from detailed investigations of the optical properties of HNe.

The available observational data on hypernovae are here reviewed and analysed, with particular emphasis on the indications that the explosions are aspherical, providing a natural link with GRB's.

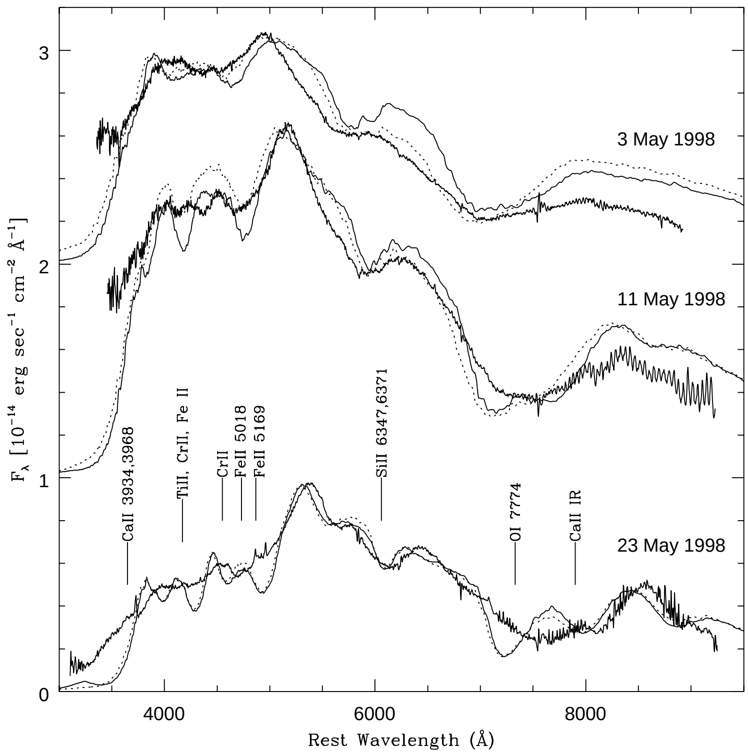

Fig. 1. Models for the photosperic epoch spectra of SN 1998bw.

2. The case of SN 1998bw

SN 1998bw was discovered in the search for the optical afterglow of GRB's, at a redshift $z = 0.0085$. The object displayed a bright, SN-like light curve, but had very unusual spectra, characterised by very broad P-Cygni lines (Galama et al. 1998). It was the understanding that the broad lines had to be due to very high-velocity material ($v \sim 30,000$ km s^{-1}) that brought us to release the assumption that all SNe explode with the same kinetic energy. Indeed, highly energetic models were required to match the observed velocities.

However, once the constant energy assumption is released, light curves become degenerate: the characteristic time-scale τ of the light curve peak of a H-free SN depends infact on the kinetic energy E, the ejected mass M_{ej} and the opacity κ, as follows (Arnett 1996):

$$\tau \propto \frac{\kappa^{1/2} M_{ej}^{3/4}}{E^{1/4}}. \tag{1}$$

Therefore, we had to test different models on the spectra, since only the spectra can resolve the discrepancy. Our best fit was for $E_{51} = 50$, $M_{ej} = 11 M_\odot$ (Figure 1). The mass of ^{56}Ni synthesised by this bright SN was very large for a core-collapse event, $\sim 0.5\,M_\odot$(Iwamoto et al. 1998; Nakamura et al. 2001). These amazing results were possibly to be expected given the coincidence with a GRB.

The later evolution to the nebular phase reserved even more surprises. The nebular spectrum was dominated by strong [O I] 6300Å, as in all SNe Ib/c, but it also showed strong [Fe II]

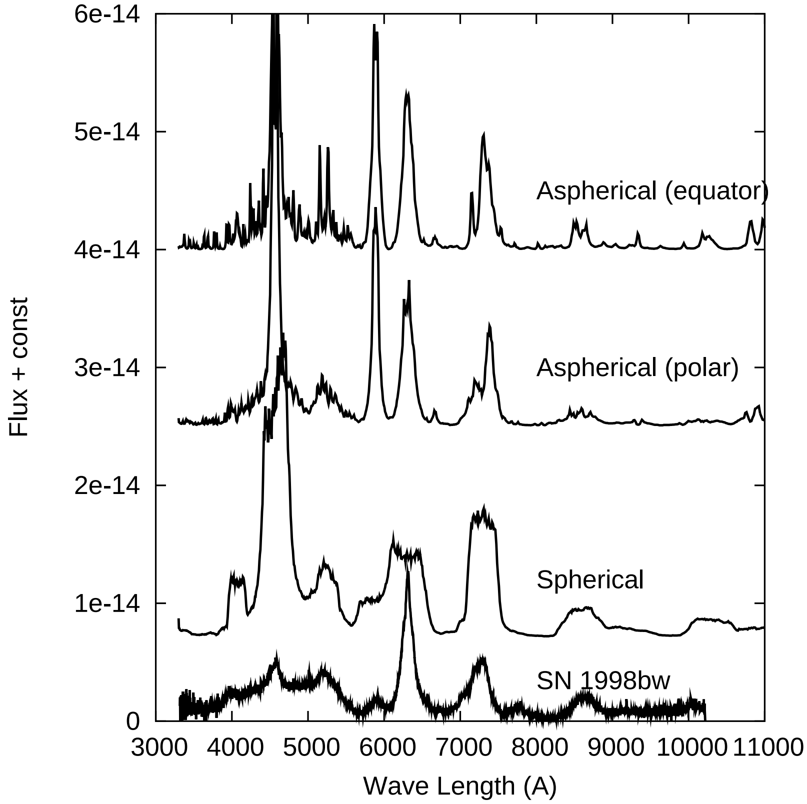

Fig. 2. Synthetic spectra of the aspherical model (E_{51} = 6) on day 200, for two orientations (polar and equatorial). A spherical model (E_{51} = 2.5) is also shown, as is the observed spectrum of SN 1998bw on day 216 (bottom).

lines, a feature of SNe Ia. Unlike SNe Ia, however, [Fe III] lines were missing. The presence of Fe lines was to be expected given unusually high ^{56}Ni production in SN 1998bw. However, the absence of [Fe III] can only be explained if the density in the Fe region is higher than that of the average model, as would be the case if the ejecta were clumped of if the Fe were concentrated in a small region, of size $\sim$ 10% of the total ejecta volume, suggestive of an asymmetric ejection.

Even more surprisingly, the [O I] line was significantly narrower than the [Fe II] ones (Mazzali et al. 2001). This cannot be realised in the onion-shell structure of 1D models. Thus, we built 2D explosion models, where we injected more kinetic energy in a specific direction – the jet. Here, burning was more effective, producing a funnel of ^{56}Ni. This is reminiscent of the typical GRB picture. We also built a 3D radiation transfer code to compute nebular spectra from this situation (Fig. 2). Not only could we successfully reproduce the observations, but we could also place constraints on the degree of asymmetry (roughly 2:1), the kinetic energy (reduced to E_{51} $\sim$ 10, and the viewing angle ($\sim$ 10 deg from the jet axis; (Maeda et al. 2002)).

The success of these models confirms that SN 1998bw was highly aspherical, supporting its link to GRB980425. The progenitor of SN 1998bw must have been a massive star, with M_{ZAMS} $\sim$ $40M_{\odot}$.

3. Other Hypernovae in GRB's

While the single case of SN 1998bw was a strong indication that GRB's and some SNe are related, much of the community (especially the GRB one) was not convinced. It took another burst, GRB030329, to win them over. A supernova was predicted to appear in this relatively nearby burst ($z = 0.167$), and was indeed observed (Stanek et al. 2003; Hjorth et al. 2003). The SN showed spectral features very similar to those of SN 1998bw (Matheson et al. 2003), and was also interpreted as an energetic explosion (Mazzali et al. 2003), although somewhat weaker than SN 1998bw.

Since the two nearest GRB's were hosted by HNe, it was at first disappointing that another nearby GRB, 031203 ($z = 0.105$) seemed too highly reddened to reveal a possible SN. However, a SN bump was eventually detected in the afterglow light curve (Tagliaferri et al. 2004). This was confirmed by Thomsen et al. (2004) and Gal-Yam et al. (2004), and, with full VLT spectral information, by Malesani et al. (2004). Although they suffer very large extinction ($E(B-V) \sim 1$), the spectra of the SN (SN 2003lw) are strikingly similar to those of SN 1998bw. Analysis of the SN is currently under way.

4. Hypernovae without GRB's

Other SNe Ic with the broad lines typical of HNe have been observed for which the connection with a GRB is unclear or even absent. The first such case, SN 1997ef, was highly enegetic, but dimmer than SN 1998bw ($E = 2 \times 10^{52}$erg; $M_{ej} = 10 M_\odot$; M(^{56}Ni) = $0.13 M_\odot$; (Mazzali et al. 2000). Its progenitor was probably a $\sim 35 M_\odot$ star. Although strong signatures of asymmetry are not present in this object, it is interesting that the photospheric phase extends to velocities well below the lower velocity of the 1D model, corresponding to the somewhat arbitrary mass cut that is imposed in 1D models to produce the required amount of ^{56}Ni. Unfortunately, nebular phase spectra of this SN are not available.

However, another SN Ic, 1997dq, is a close analogue of SN 1997ef (Matheson et al. 2001). Analysis of the nebular lines of this SN shows no significant differences in the profiles of [O I] and [Fe II], indicating that either the explosion was not strongly aspherical, or that it was viewed far from the jet axis, a possibility which we find more appealing (Mazzali et al. 2004). Maybe, had SNe 1997ef and 1997dq been viewed from a different vantage point, they would have displayed an associated GRB.

Another case of a HN without a GRB is that of the very nearby SN 2002ap. Apart from the broad lines (which are however narrower than in either SN 1998bw or SN 1997ef, indicating expansion velocities of ~ 25000km s^{-1}), this was a rather normal SN Ic, producing only 0.1 $M_\odot$of ^{56}Ni. However, the kinetic energy, $\sim 4 \times 10^{51}$ erg, was larger than the normal value, and the progenitor mass, $\sim$ 20–25 $M_\odot$, places SN 2002ap in the HN branch (Mazzali et al. 2002). In the nebular phase, only a narrow core in [O I] may be indicative of an inner density concentration where O dominates, suggestive of a mildly aspherical explosion.

Plotting the various HNe in a diagram according to KE, or M(^{56}Ni), versus progenitor mass (Figure 3), a trend for the more massive stars to produce brighter, more energetic explosions becomes evident. The GRB connection is only observed at the high-energy end of the distribution.

5. Inner Density Cores as Indications of Asphericity

Not only do many HNe show narrow [O I] lines, or line cores, but they also show a flattening in the light curve at intermediate phases (day 50-200). This is again not explained by 1D models. Maeda et al. (2003) built models where an inner high-density core acts to trap γ-rays emitted at advanced phases. This way, we could obtain good fits to the observed light curves. Again this scenario is different from the spherically symmetric one. In a jet-induced explosion, however, the equatorial region is less burned, and so it remains Oxygen-dominated, and moves out at a low velocity, similar to what the observations suggest.

6. Rates of HNe and GRB's

Given that all three nearby GRB's were hosted by HNe, it is only natural to ask what the rates of GRB's and HNe are.

Making conservative assumptions for the beaming angle, Podsiadlowski et al. (2004) derived a GRB rate $R(GRB) \sim 10^{-5}\,\mathrm{yr}^{-1}$ in a normal galaxy.

As for HNe, they are only $\sim$ 5% of all SNe Ib/c, which in turn are only $\sim$ 15% of all core-collapse SNe. Taking observational biases into account (HNe are brighter than normal SNe Ib/c), Podsiadlowski et al. (2004) derived also for HNe a rate $R(HN) \sim 10^{-5}\,\mathrm{yr}^{-1}$ per galaxy. These numbers are extremely suggestive. They are also much smaller than the expected SN rate for even the most massive stars (e.g. the rate of core-collapse SNe with progenitors more massive than $80 M_{\odot}$ is $\sim 2 \times 10^{-4}\,\mathrm{yr}^{-1}$ per galaxy). We therefore suggest that all long-duration GRB's are emitted by HN explosions.

7. Properties of HN-hosted GRB's

One striking fact is that the average energy of the GRB's with accompanying hypenovae is lower than the typical GRB energy. Perhaps this is due to a slight misalignment between the jet and the line of sight, which makes the GRB weaker as the Lorentz factor drops, without much affecting the observational properties of the associated SN (SN 1998bw/GRB980425 is a possible example of this). In this case the observed weakness of the nearby, SN-associated GRB's would be just a statistical result: it they have a finite opening angle, most GRB's will be observed off-axis. Off-axis GRB's should therefore dominate the nearby sample, but they will not be as frequent at higher redshifts as they are intrinsically fainter than on-axis ones.

While this scenario is still the subject of debate, continuing observational efforts are slowly shedding light on this mystery.

8. A normal Supernova in a GRB?

While most observations suggest that GRB's are only seen when the hypernova is extremely powerful, there is a case where an apparently normal SN, or possibly a low-energy hypernova (similar to SN 2002ap) was seen in coincidence with a normal GRB: SN 2002lt was detected in the afterglow spectrum and light curve of GRB021211, at $z \sim 1$ (Della Valle et al. 2003). Although the data are limited, the spectrum of the SN does not appear to be compatible to that of a hypernova like SN 1998bw. This might suggest that there is a real distribution of properties of the GRB's and of the SNe that host them.

9. SNe/HNe in X-Ray Flashes?

X-Ray Flashes are the weak (X-ray dominated) equivalent of GRB's. Zhang et al. (2003) suggested that they may also be produced by SN events. Finally, a SN bump was observed in the light curve of XRF030723 (Fynbo et al. 2004). Tominaga et al. (2004) interpreted the light curve as comparable to that of a weak hypernova such as SN 2002ap at a redshift $z \sim 0.6$.

Does this mean that XRF's are GRB's viewed far from the jet axis? This is possible. However, SN 2002ap synthsised much less ^{56}Ni than powerful hypernovae like SN 1998bw. Further observations and theoretical studies are needed to distinguish the effects of orientation from those of real physical differences. Possibly all SNe Ic are aspherical, and maybe all SNe Ib/c come with either a GRB or an XRF. In this scenario, XRF's might be GRB's viewed off-axis, or the result of weaker explosions, or both. In this case, the number of XRF's should far exceed that of GRB's. This might well be, since XRF's are weaker and much harder to detect. Indeed, stripping a stellar H (and He) envelope probably requires large amounts of rotation, probably a binary companion, which is also a requirement of the most popular models for making GRB's (e.g. Woosley & McFadyen (1999)), and so the fact that the ensuing stellar explosion may be significantly aspherical may not come as a great surprise.

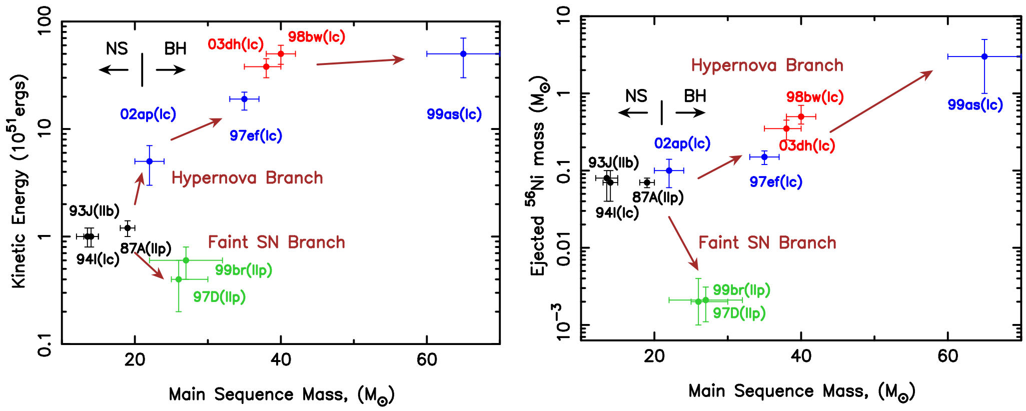

Fig. 3. Left. Explosion energies and Right. ejected ^{56}Ni mass against main sequence mass of the progenitors for several core collapse supernovae/hypernovae.

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