Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Supernovae and Gamma-ray Bursts

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Abstract. The properties of the Supernovae discovered in coincidence with long-duration Gamma-ray Bursts and X-Ray Flashes are reviewed, and compared to those of SNe for which GRBs are not observed. The SNe associated with GRBs are of Type Ic, they are brighter than the norm, and show very broad absorption lines in their spectra, indicative of high expansion velocities and hence of large explosion kinetic energies. This points to a massive star origin, and to the birth of a black hole at the time of core collapse. There is strong evidence for gross asymmetries in the SN ejecta. The observational evidence seems to suggest that GRB/SNe are more massive and energetic than XRF/SNe, and come from more massive stars. While for GRB/SNe the collapsar model is favoured, XRF/SNe may host magnetars.

Keywords. supernovae: general, supernovae: individual (SN 1997ef, 1998bw, 2002ap, 2003dh, 2003jd, 2005bf, 2006aj, 2008D), gamma rays: bursts, radiation mechanisms: general, line: formation, nuclear reactions, nucleosynthesis, abundances

1. Introduction

The connection between long-duration Gamma-Ray Bursts (GRBs) and a particular class of core-collapse Supernovae (SNe) has been established with the discovery of optically very bright SNe in positional and temporal coincidence with three of the nearest GRBs (Galama *et al.* 1998, Stanek *et al.* 2003, Malesani *et al.* 2004).

The spectra of these SNe are all very similar. They resemble closely those of Type Ic SNe, but are characterised by P-Cygni lines with very broad absorption components, indicative of the presence of material expelled at very high velocities (Fig.1). Type Ic SNe are thought to be the result of the explosion of the carbon-oxygen core of massive stars that had lost their outer hydrogen and helium envelopes prior to core collapse. The broad-lined spectra and the relatively broad light curves of the GRB-SNe suggest that they are all very energetic explosions. GRB/SNe lie at the luminous end of the distribution of SNe Ib/c, indicating a large production of ^{56}Ni ($\sim 0.5 M_\odot$, Fig 2). Because of the very large energy and their spectral characteristics, these SNe have also been called "Hypernovae" (HNe). Similarly, a connection between X-ray Flashes (XRF) and SNe Ib/c has been established (Pian *et al.* 2006, Soderberg *et al.* 2008). These SNe are also overenergetic. Here, the properties of HNe are reviewed, as is the evidence that they are aspherical events, which supports the connection with GRBs.

2. Energetics

SN spectra obtained in the early phase reflect mostly the structure of the outer part of the ejecta. The light curves and the spectra of Type Ib/c SNe must be modelled simultaneously in order to obtain an accurate estimate of the properties of the explosion (Arnett 1982). We use a Montecarlo radiation transport code (Mazzali & Lucy 1993, Lucy 1999, Mazzali 2000). The results indicate that GRB-SNe are powerful explosions

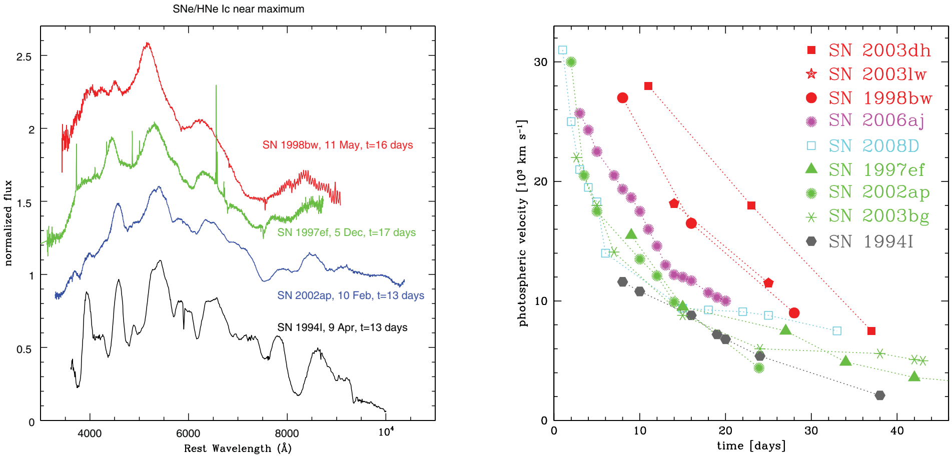

Figure 1. Left: Near-maximum spectra of SNe Ic. The increasing width of the spectral lines marks the transition to Hypernovae. **Right**: Photospheric expansion velocities of SNe Ib/c derived from spectral modelling. GRB-SNe are characterised by the highest velocities.

which ejected large quantities of matter: in the case of the prototypical SN 1998bw (associated with GRB980425) the spherically symmetric explosion kinetic energy derived from modelling is $E \approx 5 \times 10^{52}$ erg, i.e. about 50 times larger than in normal core-collapse SNe, and the ejected mass is $\sim 10 M_{\odot}$ (Iwamoto *et al.* 1998). Other GRB/SNe such as 2003dh/GRB030329 and 2003lw/GRB031203 yield similar values (Mazzali *et al.* 2003, Mazzali *et al.* 2006a, respectively), justifying the name Hypernovae. As an example, the 'prototypical' SN Ic 1994I has $M_{\rm ej} \sim 1.2 M_{\odot}$ and $E_{\rm K} \sim 10^{51}$ erg (Sauer *et al.* 2006).

The large ejecta masses indicate that the progenitor stars were very massive: including the compact remnant (most likely a black hole), the mass of the CO cores must have been $\sim 12-15 M_{\odot}$, which points to a zero-age main sequence mass of the progenitor stars of $\sim 40-50 M_{\odot}$. A very massive star origin for the SNe connected with GRBs suggests that the ejection of matter at relativistic velocities that is responsible for the emission of the GRB is linked to the formation of the black hole, and supports the scenario envisioned in the so-called "collapsar" model (McFadyen & Woosley 1999).

A number of broad-lined SNe Ic have been discovered that were not associated with GRBs. These are relatively nearby events, so the SNe were discovered optically. The two best observed such events are SNe 1997ef and 2002ap.

SN 1997ef had spectra very similar to those of SN 1998bw, and was analysed to be the very energetic explosion ($E_{\rm K} \sim 2 \times 10^{52}$ erg) of a very massive star ($M_{ZAMS} \sim 35 M_{\odot}$), ejecting however only $\sim 0.15 M_{\odot}$ of ^{56}Ni (Mazzali, Iwamoto, & Nomoto 2000).

The nearby SN 2002ap was also characterized at early times by very broad lines, suggesting again that this was a HN (Fig. 1). Just like SN 1997ef, however, SN 2002ap never became really luminous (Fig. 2). It produced a ^{56}Ni mass of $\sim 0.1 M_{\odot}$. The spectra and the rapidly evolving light curve were modelled as the explosion of a star of relatively small mass, $\sim 23 M_{\odot}$, collapsing to a black hole and ejecting $\sim 2.5 M_{\odot}$ of material with $E_{\rm K} \sim 4 \times 10^{51}$ erg (Mazzali *et al.* 2002).

3. Asphericity

A GRB is thought to be a highly beamed phenomenon, while SNe are traditionally viewed as spherical events, although this is almost certainly an oversimplification

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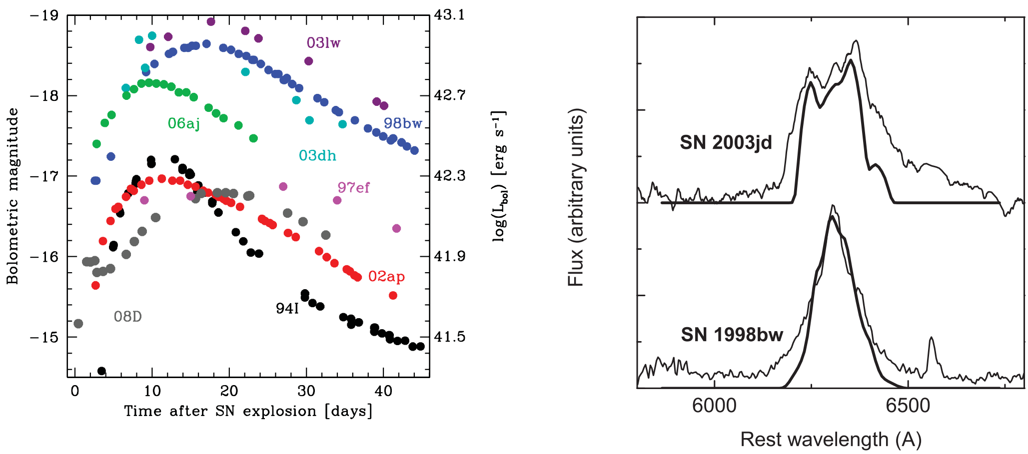

Figure 2. Left: Bolometric light curves of SNe Ib/c. GRB-SNe are at the bright end of the distribution. **Right**: The [O I] 6300Å line in the spectra of SNe 2003jd (top) and 1998bw (bottom), compared to two synthetic lines computed using the same two-dimensional model (Maeda *et al.* 2002). The viewing angle is 15 deg from the polar axis for SN 1998bw, 70 deg for SN 2003jd.

(Leonard *et al.* 2006). Although the measurement of some polarisation suggests that the ejecta may deviate from spherical symmetry, this is not easy to quantify. A much deeper view into the SN is offered by spectra obtained in the late, nebular phase. At this time, the SN nebula is optically thin. The gas is heated by the deposition of the γ-rays and fast positrons emitted in the decay chain ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe. Collisions excite the gas, which is then cooled by the emission of radiation in mostly forbidden lines. Fe II lines dominate the spectra of hypernovae in the nebular phase. This testifies to the copius production of ^{56}Ni that makes these SNe so bright. Other strong lines are those of O I and Ca II. These are typical of all SNe Ib/c and indicate a massive star origin for these SNe. Because of the low optical depth, nebular line profiles can be used to map the composition of the SN ejecta down to the lowest velocities, which are located close to the inner core of the explosion, where the black hole is formed. A careful analysis of these lines can therefore provide information about the details of the collapse and the explosion.

A close look at the nebular spectra of the first GRB-SN, 1998bw, provides interesting evidence. The [O I] 6300Å line is very strong, but it has a very sharp profile. This suggests that oxygen is concentrated at the lowest velocities. A uniform distribution would in fact give rise to a parabolic profile. A model based on this assumption (Mazzali *et al.* 2001) can reproduce the [Fe II] lines but produces a synthetic [O I] 6300Å line that is much broader than the observed one. In a massive star, oxygen is located at larger radii than heavier elements. If this mapping is preserved in a spherically symmetric explosion, then the [O I] line is expected to have a broad, flat-topped profile, as oxygen will be ejected at high velocities and it should be absent from the innermost, slow-moving part of the ejecta. This inner part should be dominated by the elements synthesised in the explosion, and in particular by iron. In a spherically symmetric explosion, therefore, Fe lines should be narrower than oxygen lines. In SN 1998bw, however, we see the opposite trend: [Fe II] lines reach velocities of at least 10000 km s^{-1}, and are much broader than [O I] 6300Å, which reaches at most 6,000 km s^{-1} (Mazzali *et al.* 2001).

This surprising observation can most simply be interpreted if we assume that iron (and therefore ^{56}Ni) was ejected at much higher velocities than oxygen. Since ^{56}Ni is

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synthesised much deeper in the star than oxygen, which is actually a product of the star's previous evolution, the simplest way to explain how it was ejected at a high velocity is to hypotesise that the explosion was highly aspherical. In such a model, kinetic energy was produced mostly along a preferred axis, which may be identified with the star's rotational axis. Consequently, in this region ^{56}Ni was preferentially synthesised. Accordingly, ^{56}Ni would be distributed mostly in a funnel, and after being ejected it remained separate from the bulk of the stellar material, which would be much less nuclearly processed and would be ejected more equatorially and with lower velocities. Thus ^{56}Ni would have a higher expansion velocity than oxygen.

2D hydrodynamic explosion models coupled to nucleosynthesis calculations show how such an explosion can occur. 3D nebular spectra based on such models not only can reproduce the observations, but also allow us to constrain our viewing angle with respect to the SN. For SN 1998bw, we find that the explosion was highly aspherical, with an energy ratio of $\sim 5:1$ in favour of the polar direction, and that an angle of $\sim 15-30$ deg with respect to the axis of the explosion gives the best fit to the observed spectrum (Maeda *et al.* 2002, Maeda, Mazzali, & Nomoto 2006). When the aspherical distribution of the kinetic energy is taken into account, we derive a total kinetic energy for SN 1998bw of $(1-2)\times 10^{52}$ erg, which is smaller than the isotropic estimate based on the early-time spectra but still an order of magnitude larger than in classical core-collapse SNe.

Given the connection between SN 1998bw and GRB980425, it is natural to assume that the axis of the explosion is also the direction along which the GRB was emitted. GRB980425 was a rather weak GRB. A slightly off-axis direction for this burst helps to explain its weakness, although it may not be sufficient (Ramirez-Ruiz *et al.* 2005).

If GRB-SNe are intrinsically aspherical, for any GRB-connected SN there should be many more SNe that are not observed to be accompanied by a GRB because their axis of ejection was not pointing towards us. We therefore began a search for the signatures of asphericity in the spectra of SNe Ib/c not connected with GRBs. This limits the sample to sufficiently nearby SNe that can be discovered optically, without the help of the GRB trigger which extends the volume of detection significantly.

We observe these SNe in the nebular phase, looking for signatures of asphericity. One easy prediction of the model discussed in the previous section is that if the axis of ejection was almost perpendicular to our line of sight, the Fe lines would be narrow, and the oxygen line broad. However, because of the disc-like distribution of oxygen, we would expect a double-peaked profile for the [O I] 6300Å line. We use data obtained with Subaru, Keck and the VLT. The most striking result so far was provided by SN 2003jd. This broad-lined SN Ic was almost as bright at peak as SN 1998bw and therefore a very promising candidate. Observations in the nebular phase clearly showed that the [O I] 6300Å line has a double-peak profile, with a large separation between the peaks. The line has a width of ~ 7000 km s^{-1}, and the peak separation is ~ 5000 km s^{-1}. Figure 2 (right) shows that the observed line profile can be reproduced just taking the two-dimensional models that we developed for SN 1998bw and computing emission profiles for an orientation close to the equatorial plane (70 deg, Mazzali *et al.* 2005). The success of this simple test confirms that hypernovae are significantly aspherical events.

Late nebular spectra of SN 1997ef, and of its twin SN 1997dq, show symmetric emission line profiles and do not suggest any major asphericity (Mazzali *et al.* 2004). In the nebular phase, the [O I] line of SN 2002ap was rather sharp, suggesting the presence of a bulk of slow-moving oxygen. Any such material cannot be explained in 1D explosion model and suggests some asphericity in the explosion (Mazzali *et al.* 2007b). The effect is however subtle and it suggests that any asphericity was not as strong as for SN 1998bw. Later, general studies found that asphericity is common among SNe Ib/c, or possibly even the norm (Maeda *et al.* 2008), but indicate that GRB/SNe are on average more aspherical than SNe with lower energy (Maurer *et al.* 2010).

Some evidence that the ejecta include a large mass at low expansion velocity is also provided by the behaviour of the light curve, which is brighter than predicted by standard one-dimensional explosion models at a SN age of 2-3 months. The inclusion of a significant mass of low-velocity material improves the light curve modelling for SNe 1998bw, 1997ef and 2002ap (Maeda *et al.* 2003, 2006). This can be taken as additional indirect evidence for an aspherical distribution of the ejecta.

An inconsistency between the mass derived from the peak of the light curve and the nebular phase is actually the norm for SNe Ic. Even SN 1994I is affected by it. Sauer *et al.* (2006) find that the nebular mass exceeds the mass needed to fit the peak of the light curve by $\sim 0.5 M_{\odot}$. Also, in all SNe Ic significant mixing-out of ^{56}Ni is required to fit the rapid rise of the light curve. This is again not predicted by 1D models and may be the result of some degree of asphericity in the explosion.

4. XRF-SNe and Magnetars

X-Ray Flashes, the soft and weak equivalent of GRBs (Heise *et al.* 2001), were suspected to have a similar origin as GRBs, and to have an associated SN. The first positive discovery of a SN associated with an XRF was the case of XRF060218/SN 2006aj (Pian *et al.* 2006). The SN was of Type Ic, and it had moderately broad lines. It was brighter than normal SNe Ic like SN 1994I, or than non-GRB-HNe such as SNe 2002ap or 1997ef, but not as bright as GRB/SNe. Its derived line velocity was also intermediate between the two groups (Fig. 1, right). Modelling indicates that the explosion that became SN 2006aj was more energetic than normal SNe, but much less so than HNe, with $E_{\rm K} \sim 2\ 10^{51}$ erg. The mass ejected was rather small, $\sim 2 M_{\odot}$, and the mass of ^{56}Ni synthesised was $\sim 0.2 M_{\odot}$. Given these small values, the progenitor star was unlikely to be very massive. Our best estimate is for a progenitor star of $\sim 20 M_{\odot}$. Such a star would probably collapse not to a black hole, but more likely to a neutron star. We therefore suggested that the high explosion energy, as well as the XRF, were the result of a magnetar event (Mazzali *et al.* 2006b). In the late phase, the emission line profiles do now show strong evidence for asphericity (Mazzali *et al.* 2007a).

Perhaps the most intriguing case of a SN which produced a Magnetar is that of the SN Ib 2005bf. This SN reached a first, fairly dim peak, but rather than decline as all other SNe Ib/c, it went through a second, brighter peak phase, reaching a second maximum about one month after the first one (Tominaga *et al.* 2005). This was followed by a sharp decline, and at late time the SN light curve fell on the expected extension of the first peak, suggesting that the first peak was the only one to be powered by ^{56}Ni decay. The second peak may then have been the result of energy injection by a magnetar in an aspherical explosion (Maeda *et al.* 2007).

Another interesting case of a SN associated with an X-ray transient was that of XRF080109/SN 2008D. This SN was discovered following the serendipitous detection of an X-ray burst (Soderberg *et al.* 2008). One of the new aspects of this SN is that it was of Type Ib rather than Ic. Initially, the SN displayed a broad-lined SN Ic spectrum, but later He I lines developed. This is predicted thoretically if a sufficiently large mass of helium is present in the ejecta: He I lines can only develop following non-thermal excitation processes, which require that the ejecta are not very dense (Mazzali & Lucy 1998). The nature of the X-ray transient is debated. Soderberg *et al.* (2008) suggest that it was

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Table 1. Properties of GRB-SNe.

GRB/SN	E_K 10^{51} erg	M(^{56}Ni) $M_\odot$	M_{ej} $M_\odot$	M(CO) $M_\odot$	M_{ZAMS} $M_\odot$	Reference
GRB 980425/SN 1998bw	50 ± 5	0.38-0.48	11 ± 1	14 ± 1	35-45	Iwamoto *et al.* 1998
GRB 030329/SN 2003dh	40 ± 10	0.25-0.45	8 ± 2	11 ± 1	30-40	Mazzali *et al.* 2003
GRB 031203/SN 2003lw	60 ± 10	0.45-0.65	13 ± 2	16 ± 1	40-50	Mazzali *et al.* 2006a
XRF 060218/SN 2006aj	2 ± 0.5	0.20-0.25	2 ± 0.5	3.5 ± 0.5	18-22	Mazzali *et al.* 2006b
XRF 080109/SN 2008D (Ib)	7 ± 1	0.07-0.11	7 ± 2	8 ± 2	25-30	Mazzali *et al.* 2008
SN 1997ef	20 ± 4	0.13-0.17	8 ± 2	11 ± 1	30-40	Mazzali *et al.* 2000
SN 2003bg (IIb)	5 ± 1	0.12-0.20	4 ± 1	5 ± 1.5	20-27	Mazzali *et al.* 2009
SN 2002ap	4 ± 1	0.09-0.10	2.5 ± 0.5	5 ± 1	21-25	Mazzali *et al.* 2002
SN 1994I	1 ± 0.2	0.07-0.08	1.2 ± 0.2	2 ± 0.5	14-16	Sauer *et al.* 2006

the result of the breakout of the shock that exploded the star, and that it is a common phenomenon. Mazzali *et al.* (2008) offer a different interpretation. Modelling of the light curve and spectra indicate that SN 2008D was not a typical SN Ib/c, but rather a HN, as indicated by the large $E_K \sim 7 \times 10^{51}$ erg, and the massive ejecta ($M_{ej} \sim 5 M_\odot$; see also Tanaka *et al.* 2009a). The progenitor of SN 2008D may have been a star of $\sim 25 M_\odot$, at the border between black hole and neutron star formation. Therefore the ejection of relativistic material was not unlikely. However, in the case of SN 2008D a relativistic jet may have been weak, and it would also be affected by the presence of the massive ($\sim 2 M_\odot$) He envelope, so that it may only have emerged as a subrelativistic outlow, mimicking the behaviour of the breakout of a shock through the stellar envelope. Such a scenario receives strong support by the nebular spectrum of SN 2008D, which indicates large asphericity (Tanaka *et al.* 2009b).

5. Discussion

The link between energetic, broad-lined type Ic SNe (Hypernovae) and GRBs is established conclusively. The relative rates of GRB and HNe are in good agreement (Podsiadlowski *et al.* 2004), although it is not clear that all HNe make a GRB (Soderberg *et al.* 2006). The exact definition of a HN is not agreed upon. Broad lines and high E_K are an ingredient, but an accompanying GRB is a feature of possibly only the most massive SNe Ic. Presence of a He envelope may quench any jet. Stripping the hydrogen and helium envelopes may require interaction in a binary system.

At lower masses, Type Ic SNe that produce neutron stars may also give rise to an XRF if the neutron star is born spinning rapidly – a magnetar (Mazzali *et al.* 2006b). As in the case of GRBs, this may require the most massive stars that collapse to a neutron star, with ZAMS mass near $20 - 23 M_\odot$.

There is an apparent relation between stellar ZAMS mass, explosion kinetic energy, and luminosity of the SN, as shown in Fig.3 (Nomoto *et al.* 2005).

Nebular spectra can be used to derive the asphericity of the SN explosion and even to determine, albeit only approximately, the direction of the jet axis with respect to our line of sight. This may help us understand the extremely variable properties of the SN-related GRBs, in the face of an amazingly narrow distribution of the properties of the GRB-related SNe (Table 1). Evidence that HNe may occur even in Type IIb SNe (where a thin layer of H has also been preserved) has also been found (Mazzali *et al.* 2009).

A number of questions then arise.

1. Are there minimum requirements for the presence of a GRB in terms of M_{ej}, M(^{56}Ni) and E_K? GRB/SNe are both more energetic and brighter (i.e. they produced more ^{56}Ni) than all other SNe Ib/c (Fig. 3). Recent examples, such as the very broad-lined SN Ic

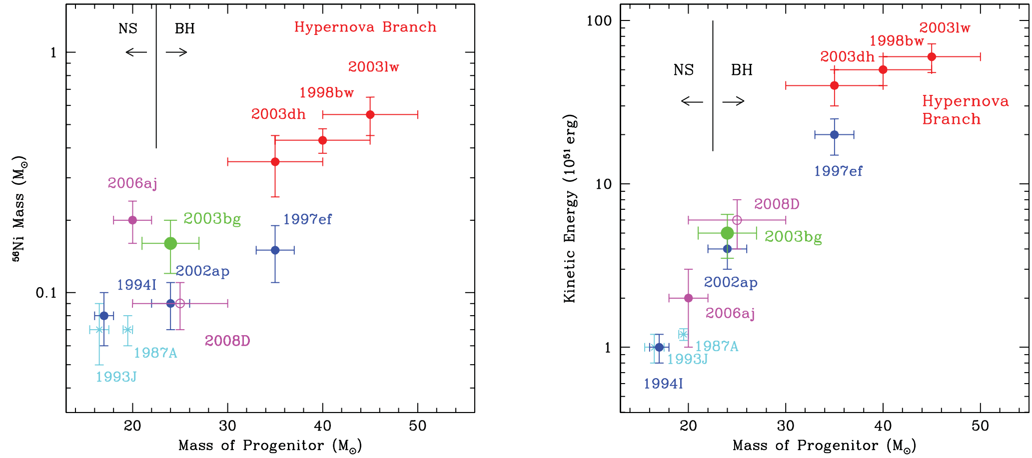

Figure 3. Relation between ^{56}Ni mass, SN kinetic energy and progenitor mass.

SN 2010ah (Corsi *et al.* 2011), or the SN Ic 2010bh, linked with XRF100316D (Cano *et al.* 2011) have not violated this rule. Is this a strict requirement, and if so, why?

2. Where are the off-axis GRB-SNe? Depending on the actual frequency of these events, the volume that we can sample with optically discovered SNe may be too small to include a significant number of GRB-SNe. Additionally, it is possible that not all HNe Ic produced a GRB. Our search indicates that a few SNe Ib/c were aspherical events viewed off-axis. A continued search for the signatures of asphericity in SN explosions on the one hand, and traces of the ejection of material at relativistic velocities on the other are necessary to establish the actual rate of GRB-SNe with respect to that of hypernovae and their fraction relative to all SNe Ic. Alternatively, the jetted nature of the relativistic outflow of nearby GRB/SNe needs to come in question.

3. Why are the GRB-SNe so similar while the SN-GRBs are so different? This may be partly related to orientation, and a study such as that discussed above can also be useful to clarify this apparently puzzling state of affairs. We should also keep in mind that a clear association between GRBs and SNe has only been established for the nearest GRBs. These events may be on average weaker than cosmological ones, and more numerous. All GRB-SNe so far seem to have had progenitors of $\sim 40 M_{\odot}$, while the mass of the SNe associated with an X-Ray Flash is $\sim 20 M_{\odot}$ (Mazzali *et al.* 2006b). As the volume sampled by cosmological GRB is much larger, it is possible that more massive stars contribute to the observed GRBs, which may be intrinsically more powerful.

4. What is the role of Magnetars? Can they contribute kinetic energy to the SN explosion, and can they also help synthesize some ^{56}Ni? It has also been suggested that Magnetars are responsible for most GRB/SNe (Woosley 2010).

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Discussion

O'BRIEN: Where is the mass boundary between progenitors that make a NS or a BH?
P.M.: It is very unclear. The line on my plot is the traditional place to put it.

KULKARNI: Could asphericity be due simply to large convective bubbles rather than a jet? For example, SN 2002ap shows no sign of being a HN.
P.M.: This is possible in the lower energy SNe, but unlikely in HNe. The inferred degree of asphercity is much larger in HNe. Asphericity is higher in the deeper layers, hence SNe Ic tend to be more aspherical than SNe Ib etc. SN 2002ap had enough mass at high velocity to produce broad lines, hence we call it a HN. It however did not have much mass at $v \sim 0.1c$ or higher, as our spectral models showed, and may therefore not have been able to produce a GRB.

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