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SUPERNOVAE AND GAMMA-RAY BURSTS

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RESUMEN

La evidencia observacional indica que el flujo eyectado de material en muchas supernovas (SN), posiblemente en todas ellas, no es esférico. Aquí revisamos la evidencia en SNs tipo Ic asociadas con los estallidos de rayos gamma (GRB-SNe). Se piensa que estas SNs se originan en estrellas muy masivas. Ellas son particularmente propicias para estudiar los detalles del proceso de colapso ya que no están dentro de una espesa envoltura de hidrógeno, con un núcleo interno de carbono-oxígeno expuesto, cerca del sitio de colapso, y a causa de la asociación con los GRBs. En las estrellas más masivas ($M \approx 40M_{\odot}$), las observaciones pueden indicar que las explosiones de SN están provocadas por el flujo de masa hacia el remanente compacto, y que este remanente debe ser un hoyo negro. Esto parece ser un requerimiento necesario para que una SN también genere un GRB. Para estrellas menos masivas ($M \approx 20M_{\odot}$), el remanente puede ser una estrella de neutrones y la actividad magnética puede ser reponsable de la energética explosión y del destello de rayos X.

ABSTRACT

Observational evidence indicates that the outflow of material in many, possibly even in all Supernovae, is not spherical. Here we review the evidence in Type Ic SNe associated with Gamma-Ray Bursts (GRB-SNe). These SNe are thought to originate in very massive stars. They are particularly suited to study the details of the collapse process because they are not enshrouded in a thick hydrogen envelope, exposing the inner carbon-oxygen core, near the site of collapse, and because of the link with GRBs. In the more massive stars ($M \approx 40M_{\odot}$), observations may be interpreted to indicate that the SN explosion is driven by the mass inflow into the compact remnant, and that this remnant must be a Black Hole. This seems to be a necessary requirement for the SN also to generate a GRB. For less massive stars ($M \approx 20M_{\odot}$), the remnant may be a neutron star and megnetic activity may be responsible for the energetic explosion and an X-ray Flash.

Key Words: **GAMMA RAYS: BURSTS — SUPERNOVAE**

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 the three nearest GRBs (Galama et al. 1998; Stanek et al. 2003; Malesani et al. 2004). The spectra of the SNe are very similar to one another, and are characterised by P-Cygni lines with very broad absorption components, indicative of the presence of material expelled at very high velocities (Figure 1). The spectra resemble most closely those of Type Ic SNe. These SNe are thought to be the result of the explosion of the carbon-oxygen core of a massive star, which had lost its outer hydrogen and helium envelopes prior to the collapse of the core. Analysis of the spectra and the light curves of the GRB-SNe suggests that they are all very energetic explosions, which ejected large quantities of matter: typically, the explosion energy is $E \sim 5\ 10^{52}$ erg, which is about 50 times larger than in normal core-collapse SNe, and the ejected mass is $\sim 10M_{\odot}$(Iwamoto et al. 1998; Mazzali et al. 2003; Mazzali et al. 2006a). Because of the very large energy, these SNe have also been called "Hypernovae" (HNe). The luminosity and expansion velocities of HNe tend to be at the high end of the distribution of SNe Ic (Figures 2 and 3).

These values indicate that the progenitor stars were very massive: including the compact remnant (most likely a black hole), the mass of the CO core must have been $\sim 13M_{\odot}$, which points to a zero-

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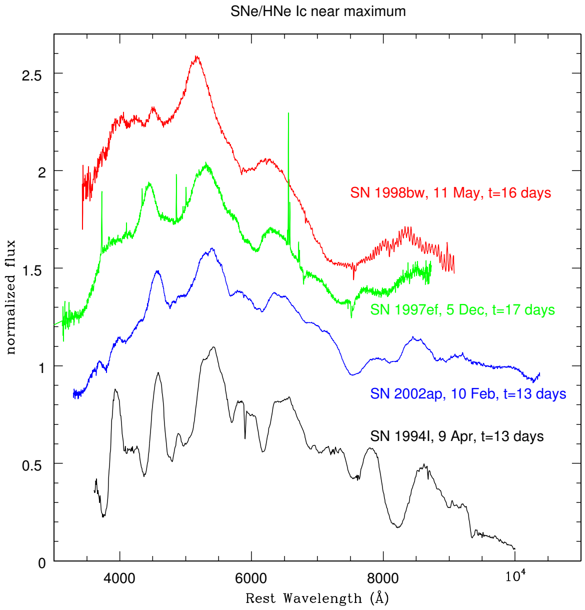

Fig. 1. Near-maximum spectra of SNe Ic. The increasing width of the spectral lines marks the transition to Hypernovae.

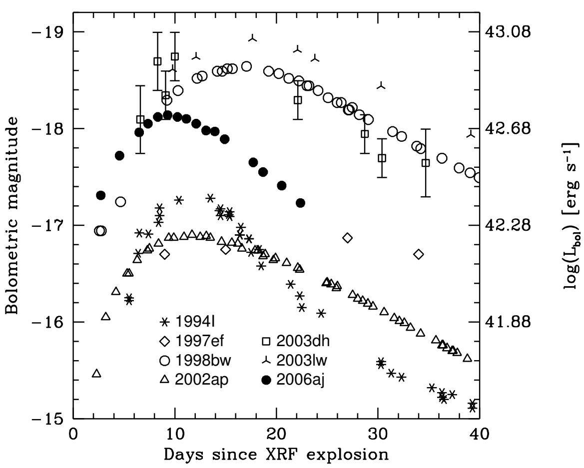

Fig. 2. Bolometric light curves of SNe Ic. The GRB-SNe are at the bright end of the distribution.

age main sequence mass of the progenitor star of $\sim 40 M_{\odot}$. 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).

However, a link is missing: 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 (Leonard et al. 2006). In this paper, we review the evidence that GRB-SNe are themselves aspherical events, although not as much so as GRBs. This evidence supports the GRB-SN connection.

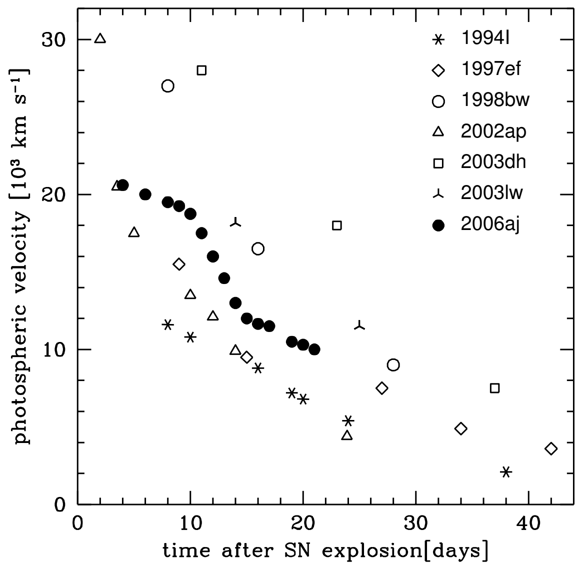

Fig. 3. Photospheric expansion velocities of SNe Ic derived from spectral modelling. GRB-SNe are characterised by the highest velocities.

2. EVIDENCE OF ASPHERICITY IN GRB-SNE

The spectra of the SNe obtained in the early phase reflect mostly the structure of the outer part of the ejecta. Although the measurement of some polarisation is suggestive 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 fastγ-rays and 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. The lines that dominate the spectra of hypernovae in the nebular phase are those of Fe II, which witnesses the copius production of ^{56}Ni that makes these SNe so bright, and lines of O I and Ca II, which are typical of all SNe Ic. Because of the low optical depth, the profiles of the nebular lines can be used to map the composition of the SN ejecta down to the lowest velocities, which are produced 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-explosion event.

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 mased 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 (Figure 4). Actually, 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 the iron (and therefore ^{56}Ni) was ejected at much higher velocities than oxygen. The simplest scenario that could lead to this is that the explosion that made SN 1998bw was very aspherical. Since ^{56}Ni is synthesised much deeper in the star than oxygen, which is actually a product of the star's previous evolution, the simpler 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 the axis of the explosion, and in this region ^{56}Ni was preferentially synthesised. Accordingly, ^{56}Ni was produced mostly in a funnel, most likely near the poles of the star, and after it was ejected it remained separate from the bulk of the stellar material, which was not nuclearly processed and was ejected more equatorially and at lower velocities. The net result of this is that ^{56}Ni had a higher expansion velocity than oxygen. Some evidence that the inner part of the ejecta have large mass and low expansion velocity is also obtained from 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 (Maeda et al. 2003, 2006a).

Two-dimensional hydrodynamic explosion models coupled to nucleosynthesis calculations show how such an explosion can occur. Three-dimensional 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, 2006b). 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. In addition, we found that the light curve can be well reproduced by the same model (Maeda et al. 2006a).

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).

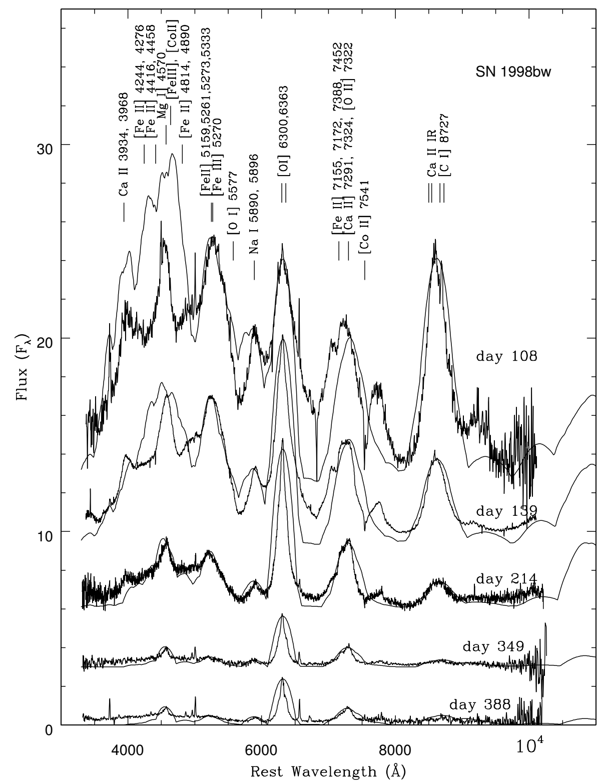

Fig. 4. The observed spectra of SN 1998bw from 12 August 1998 to 21 May 1999 compared to a set of synthetic spectra. All spectra have been shifted arbitrarily.

3. ASPHERICITY IN NON-GRB HYPERNOVAE

If GRB-SNe are intrinsically aspherical, we can expect that for any GRB-connected SN there will be many more SNe that are not observed to be accompanied by a GRB because their axis of ejection was pointing too far away from our line of sight. We therefore began a search for the signatures of asphericity in the spectra of SNe Ic not connected to GRBs. This limited the sample to sufficiently nearby SNe that can be discovered optically, without the help of the GRB trigger that extends the volume of detection significantly.

In view of the discussion above, this search has the following strategy: first we identify hypernovae among SNe Ibc by their high peak luminosity and the broad absorption lines. We then 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 may expect a double-peaked profile for the [O I] 6300Å line.

Our programme is performed with Subaru, Keck, and VLT. The most striking result so far was that provided by SN 2003jd. This was a broad-lined SN Ic, 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. The line had a width of $\sim 7000\,\mathrm{km\ s^{-1}}$, and the two peaks were separated by $\sim 5000\,\mathrm{km\ s^{-1}}$. Figure 5 shows how we could reproduce the observed line profiles by 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.

Whether SN 2003jd also produced a GRB is debated. The lack of a radio detection (Soderberg et al. 2006) was taken to imply that no relativistic ejecta were produced. However, this is based on a number of limiting assumptions regarding the pre-SN mass-loss history of the progenitor star, and the lack of a radio and X-ray detection of a possible GRB may simply be the consequence of a smaller mass-loss rate than assumed, or a longer time for the relativistic jet to become sub-relativistic and to spread isotropically.

A number of broad-lined SNe Ic have been discovered in the last 10 years taht were not associated

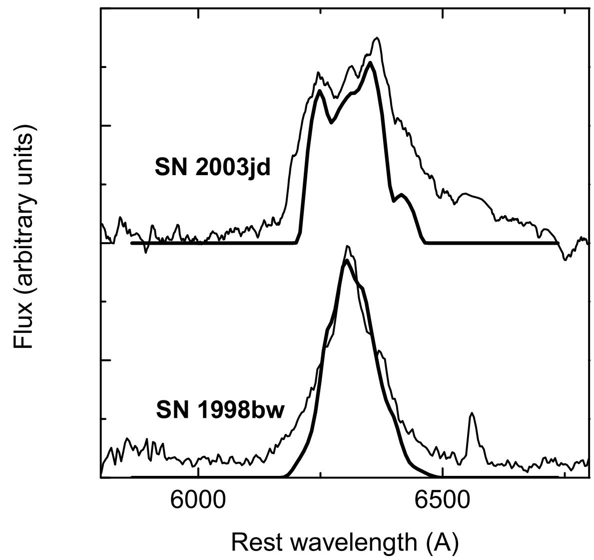

Fig. 5. The [O I] 6300Å line in the spectra of SNe 2003jd (top) and 1998bw (bottom), compared to two synthetic lines computed using the same two-dimensional model (Maeda et al. 2002). In the case of SN 1998bw the explosion is viewed at an angle of 15 deg from the polar axis, while for SN 2003jd the angle is 70 deg.

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 ($E_\mathrm{K} \sim 2 \times 10^{52}$ erg) of a very massive star ($M_{ZAMS} \sim 35 M_\odot$), ejecting however only $\sim 0.15 M_\odot$ of ^{56}Ni (Mazzali et al. 2000). 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).

The very nearby SN 2002ap was also characterized by very broad lines near maximum, suggesting again that this was a HN (Figure 1). Just like SN 1997ef, however, SN 2002ap never became really luminous (Figure 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, $\sim 23 M_\odot$, colapsing to a black hole and ejecting $\sim 2.5 M_\odot$ of material with $E_\mathrm{K} \sim 4 \times 10^{51}$ erg (Mazzali et al. 2002). In the nebular phase, the [O I] line was rather sharp, sugesting 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. The effect is however subtle and it suggests that any asphericity was not as strong as for

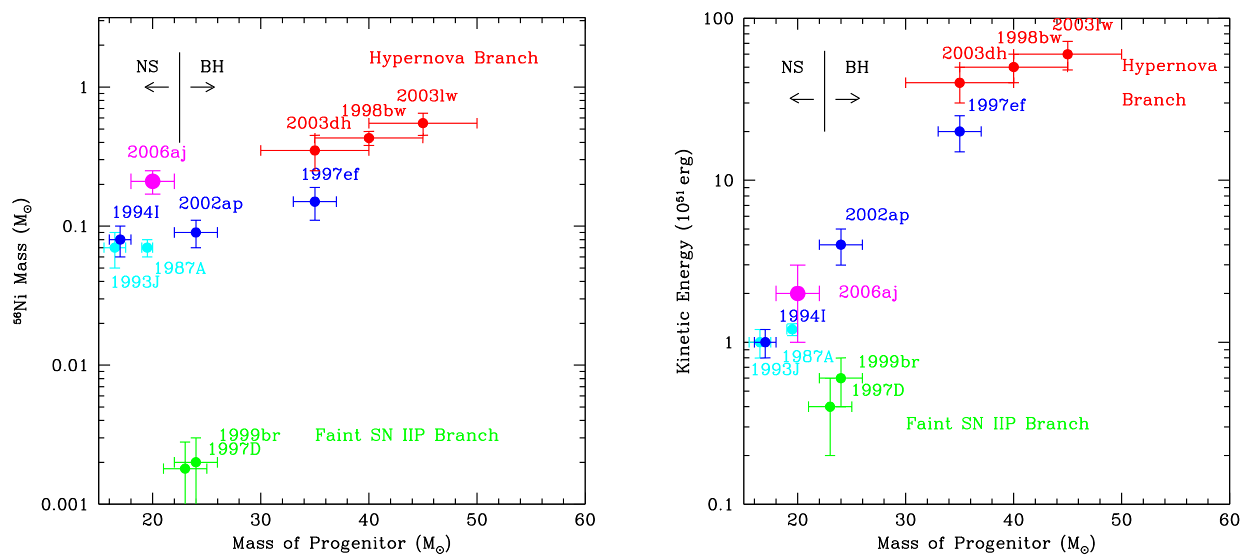

Fig. 6. Relation between ^{56}Ni mass, explosion kinetic energy, and mass of the progenitor star.

SN 1998bw. A slowly declining phase of the light curve at epochs of 2-4 months was observed in both SN 1997ef and 2002ap, and the presence of a significant mass of low-velocity material improves the light curve modelling (Maeda et al. 2002).

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 the low-mass ($\sim 1 M_{\odot}$), normal-energy ($\sim \times 10^{51}$ erg), 'prototypical' SN Ic 1994I is affected by this. 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. 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). A GRB is a feature of possibly only the most massive SNe Ic. Stripping the hydrogen and helium envelopes may require interaction in a binary system. At lower mass, 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 can collapse to a neutron star, with ZAMS mass near $20 M_{\odot}$. There is an apparent relation between stellar ZAMS mass, explosion kinetic energy, and luminosity of the SN, as shown in Figure 6 (Nomoto et al. 2005). It has even been speculated that the luminosity of the SN (i.e., the mass of ^{56}Ni synthesised) may bcorrelate with the strength of the GRB itself (Li 2006).

The SN 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).

A number of questions then arise.

1. Where are the off-axis GRB-SNe? Depending of the actual frequency of these events, it is quite possible that the volume that we can sample with optically discovered SNe is too small to include a significant number of GRB-SNe. It is possible that not all bright and broad-lined (hence energetic) SNe Ic produced a GRB. Our search indicates that a few SNe Ibc 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.

2. 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 dis-

TABLE 1

PROPERTIES OF GRB-SNE.

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

cussed 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 $\sim 40M_\odot$, while the mass of the one SNe associated with an X-Ray Flash is $\sim 20M_\odot$ (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.

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