Supernovae Shedding Light on Gamma-Ray Bursts

M. Della Valle

INAF-Arcetri Astrophysical Observatory, Largo E. Fermi 5, Firenze (Italy)

Summary. — We review the observational status of the Supernova (SN)/Gamma-Ray Burst (GRB) connection. In section 2 we provide a short summary of the observational properties of core-collapse SNe. In sections 3-6 we review the circumstantial evidences and the direct observations that support the existence of a deep connection between the death of massive stars and GRBs. Present data suggest that SNe associated with GRBs form a heterogeneous class of objects including both bright and faint Hypernovae and perhaps also ‘standard’ Ib/c events. In section 7, we provide an empirical estimate of the rate of Hypernovae, for a “MilkyWay-like” galaxy, of about \( \sim 2.6 \times 10^{-4} \) yr\(^{-1} \) that may imply the ratio GRB/Hypernovae to be in the range \( \sim 0.03 - 0.7 \). In the same framework we find the ratio GRB/SNe-Ibc to be \( \sim 0.008 \div 0.05 \). In section 8 we discuss the possible existence of a lag between the SN explosion and the associated gamma-ray event. In the few SN/GRB associations so far discovered the SN explosions and GRB events appear to go off simultaneously. In section 9 we present the conclusions and highlight the open problems that Swift hopefully will allow us to solve.

PACS 98.70 – Gamma-Ray sources; Gamma-Ray Bursts.

1. – Introduction

Gamma Ray Bursts are sudden and powerful flashes of gamma-ray radiation that occur randomly in the sky at the rate of about one per day (as observed by the BATSE instrument). The distribution of the durations at MeV energies ranges from \( T \sim 10^{-3} \) s to about \( 10^3 \) s and is clearly bimodal (Kouveliotou et al. 1993), with “long” bursts characterized by \( T > 2 \) s. In the original discovery paper, Klebesadel, Strong & Olson (1973) pointed out the lack of evidence for a connection between GRBs and Supernovae (SNe), as proposed by Colgate (1968), but they concluded that “... the lack of correlation between gamma-ray bursts and reported supernovae does not conclusively argue against such an association...”. This point remained a mystery for almost three decades and only at the end of the 1990s the discovery of GRB afterglows (Costa et al. 1997, van Paradijs et al. 1997, Frail et. al 1997) at cosmological distances (Metzger et al. 1997) and the discovery of SN 1998bw in the error-box of GRB 980425 (Galama et al. 1998) have started shedding light upon the nature of GRB progenitors.
2. – Core-Collapse Supernovae

Type-II SNe represent about 70% of the exploding stars in the universe (Cappellaro et al. 1999, Mannucci et al. 2005). They have never been discovered in elliptical galaxies and this led to the idea that their progenitors should be massive stars > 8 – 10$M_{\odot}$ (e.g. Iben & Renzini 1983) that undergo core-collapse. This fact was perceived by Baade and Zwicky (1934a, 1934b): “a supernova represents the transition of an ordinary star into a neutron star consisting mainly of neutrons”. The gravitational binding energy of the imploding core ($\sim 10^{53}$ erg) is almost entirely (99%) released as neutrinos whereas only $\sim 10^{51}$ erg are converted in kinetic energy of the ejecta and a very tiny fraction, $\sim 10^{49}$ erg, in luminous energy.

The spectroscopic classification of SNe dates back to Minkowski (1941): “Spectroscopic observations indicate at least two types of supernovae. Nine objects form an extremely homogeneous group provisionally called “type I”. The remaining five objects are distinctly different; they are provisionally designed as type II. The individual differences in this group are large...”. Particularly type-II SNe include objects with prominent hydrogen lines while type-I class is defined by the lack of hydrogen in the spectra. Nowadays we designated as type-Ia those type-I SNe that are characterized by a strong absorption observed at $\sim 6150$ Å (attributed to the P-Cyg profile of Si II, $\lambda\lambda 6347, 6371$) and lack of H. The absence of H, and the fact that these SNe are discovered also in elliptical galaxies, hint that they arise from a different explosive phenomenon, such as the thermonuclear disruption of a white dwarf approaching the Chandrasekhar limit, after accreting material from a binary companion or coalescing with it (e.g. Livio 2001 and references therein). The spectroscopic classification of SNe has been substantially reviewed in the last 20 years (e.g. Filippenko 1997a, Hamuy 2003) and six distinct classes of core-collapse SNe can be recognized from their spectra obtained close to maximum light.

a) Normal type II. SNe with prominent Balmer lines flanked by P-Cyg profiles (“...the spectrum as a whole resembles that of normal novae in the transition stage...”, Minkowski 1941). These SNe are believed to undergo the collapse of the core when the progenitor star still retains a huge H envelope ($\sim 10 – 60M_{\odot}$, Hamuy 2003). The most outstanding feature is the H$\alpha$ line flanked by a P-Cyg profile. These SNe show a very high degree of individuality that is reflected in wide range of observed line widths, that indicates the existence of a significant range in expansion velocities.

b) Interacting type II. SNe belonging to this class show strong H lines in emission without absorptions. Chugai (1997) pointed out that these SNe undergo a strong interaction with a “dense wind” generated by the progenitor during repeated episodes of mass loss prior to exploding (e.g. SN 1994aj Benetti et al. 1998). Their spectra are dominated by a broad H$_{\alpha}$ line (FWHM$\sim 10000$ km/s) sometimes superimposed by a narrow emission component (FWHM$\sim 200 – 300$ km/s). In this case the SN is dubbed as II-n (“narrow”, Schlegel 1990). Sporadically a narrow P-Cyg profile can be observed as in Benetti et al. (1999) and in this case the designation II-d indicates “double profile”.

SNe belonging to class a) and b) can be crudely grouped into two photometric varieties: type II-P (plateau) and type II-L (linear) (Barbon, Ciatti & Rosino 1979, Doggett & Branch 1985). Shortly after the explosion all SN light curves are powered by the radioactive decay of $^{56}$Ni $\rightarrow$ $^{56}$Co and later on by $^{56}$Co $\rightarrow$ $^{56}$Fe, therefore the respective luminosities are mostly determined by the amount of $^{56}$Ni that has been synthesized during the SN explosion. The magnitudes at maximum of type-II SNe span a range of about 5 mag (see Patat et al. 1994), which may imply that the amount of $^{56}$Ni produced
in SN explosions varies by a factor 100 ($\sim 0.002 \div 0.2 M_\odot$, e.g. Turatto et al. 1998).

c) Type-Ib/c. This class of SNe was first noted by Bertola (1964) “It is well known that one of the most conspicuous features in the visual spectrum of type I supernovae is a very deep absorption at $\lambda$ 6150 Å...Such absorption is missing in the present SN$^{(1)}$”. The criteria to classify the members of this subclass of type-I SNe just as ‘peculiar’ objects were adopted in the literature for the following 20 years. Only in the mid-1980s (Panagia 1985, Elias et al. 1985; Uomoto & Kirshner 1985; Wheeler & Levreault 1995) it was realized that sufficient observational differences did exist to justify having two separate classes of objects (see Matheson et al. 2001 for a recent comprehensive study).

Type-Ib SNe are characterized by spectra with no presence of H (Fig. 1 left panel) or very weak lines (Branch et al. 2002) and strong He I lines at $\lambda\lambda$ 4471, 5876, 6678 and 7065 Å (Porter & Filippenko 1987). Type-Ic (Wheeler & Harkness 1986) are characterized by weak or absent H and Si II $\lambda\lambda$ 6347, 6371 lines, and no prominent (if not totally absent) He lines. They show Ca II H & K, NIR Ca II triplet and O I lines with P-Cyg profiles. Type-Ib/c SNe have been so far observed only in late type galaxies and their most outstanding spectroscopic feature is the lack of H in the spectra. Both facts suggest that their progenitors are massive stars, possibly in binary systems (e.g. Mirabel 2004, Maund et al. 2004), which undergo the collapse of their cores after they have lost the respective H or He envelopes, via strong stellar wind or transfer to a binary companion via Roche overflow. This scenario is fully consistent with observations at radio wavelengths that reveal the existence of a strong radio emission due to the interaction of the ejecta with a dense pre-explosion stellar wind ($10^{-5/-6} M_\odot$ yr$^{-1}$)/established circumstellar medium, produced by the progenitor (Weiler et al. 2002).

Fig. 1. – **Left panel.** Optical spectra of type-Ib and type-Ic SNe obtained a few weeks past maximum. **Right panel.** Optical spectra at maximum light of Hypernovae, compared with the prototypical SN-Ic 1994I. Plots from Hamuy 2003.

$^{(1)}$ SN 1962L in NGC 1073
d) **Type-IIb.** Members of this meagre class of SNe are objects that evolve from type-II, as inferred by observations of H lines in the spectra at maximum light, into type-Ib (lack of H lines during the nebular stage, for example). The precursors are thought to be massive stars that still retain a thin H envelope prior to exploding. Prototypical objects of this SN class are SN 1987K (Filippenko 1988) and SN 1993J (Swartz et al. 1993; Filippenko, Matheson & Hot 1993). The discovery of these SNe provides a robust piece of evidence for the existence of a continuous sequence of SNe having decreasing envelope mass, i.e. type II–IIb–Ib–Ib/c–Ic.

e) **Hypernovae** (Fig. 1, right panel). In 1998 a ‘weird’ SN (1998bw) was discovered to be spatially and temporally coincident (chance probability $P \sim 10^{-4}$) with the Gamma Ray Burst 980425 (Galama et al. 1998). The early spectroscopic classification of this object was not an easy task, indeed. The spectrum at maximum light was: “...not typical of type-Ic supernovae; indeed, the spectrum does not match any of the known spectral classes, but perhaps ‘peculiar type Ic’ is the best choice at this time” (Filippenko 1998). Only observations at late stages (Patat et al. 2001, Stathakis et al. 2000, Sollerman et al. 2000) have allowed to unambiguously classify SN 1998bw as type Ib/c. To date (January 2005) 10 more SNe (see tab. II) have been found to display spectra, at maximum light, with similar characteristics, i.e. an almost featureless continuum, characterized by broad undulations, without H lines. The comparison with the prototypical Ic event, SN 1994I (Filippenko et al. 1995, Clocchiatti et al. 1996), has confirmed that these ‘peculiar’ objects are SNe-Ib/c with expansion velocities of the order of 30-40000 km/s that lead to large Doppler broadening and blending of the emission lines. The very high expansion velocities of the ejecta suggest that these SNe are hyper-kinetic (Nomoto et al. 2001), although not necessarily hyper-luminous, indeed exhibiting a broad range of luminosities, $M_B \sim -17.0 \div -19.5$, at maximum light (see Fig 2). These objects have been dubbed as **Hypernovae** (note that this designation was used by Paczyński (1998) with a different meaning).

### 3. - The SN/GRB Connection: Circumstantial Evidences

Before 2003 the existence of a connection between SNe and long duration GRBs was supported by several lines of evidence, even if none of them was really conclusive.

1) SN 1998bw was the first SN discovered spatially and temporally coincident with a GRB (GRB 980425; Galama et al. 1998). Unexpectedly, SN 1998bw was discovered not at cosmological distances, but in the nearby galaxy ESO 184-G82 at $z = 0.0085$. This implied that GRB 980425 was underenergetic by 4 orders of magnitudes with respect to typical “cosmological GRBs”. Moreover, the absence of a conspicuous GRB afterglow contrasted with the associated SN, which was extremely energetic, had expansion velocities a factor 3-4 higher than those of normal Ib/c SNe and was characterized by a peak luminosity of $\sim 10^{44}$ erg s$^{-1}$ (for a distance to SN 1998bw of $\sim 40$ Mpc). This is about 10 times brighter than typical SNe Ib/Ic (Clocchiatti & Wheeler 1997), therefore suggesting that a large amount of $^{56}$Ni must have been synthesized in the SN explosion (Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999). The theoretical modeling of the light curve and spectra suggests that SN 1998bw can be well reproduced by an extremely energetic explosion of an envelope-stripped star, with a C+O core of about $\sim 10 M_\odot$, which originally was $\sim 40 M_\odot$ on the main sequence (see Tab. I). This picture is consistent with the radio properties of SN 1998bw, which can be explained as due to the interaction of a mildly relativistic ($\Gamma \sim 1.6$) shock with a dense circumstellar medium.
(Kulkarni et al. 1998, Weiler et al. 2002) due to a massive progenitors that has entirely lost its H envelope.

Höflich, Wheeler & Wang (1999) presented an alternative picture based on the hypothesis that all SNe-Ic are the results of aspherical explosions. In this case the apparent luminosity of the SN may vary up to 2 mag, according to different combinations of the geometry of the explosion and line of sight of the observer. This result can explain the high luminosity at maximum of SN 1998bw, without calling for a dramatic overproduction of $^{56}\text{Ni} (\sim 0.2 M_\odot ^{56}\text{Ni})$ and would allow SN 1998bw to have an explosion energy ($\sim 2 \times 10^{51}$ erg) similar to that of ’normal’ core-collapse supernovae. Maeda et al. (2002), after analyzing the line profiles in late time spectra of SN 1998bw, also give some support to the idea that SN 1998bw was the product of an asymmetric explosion viewed from near the jet direction (yet characterized by high kinetic energy, of $\sim 10^{52}$ erg). The idea that Hypernovae and more generally SNe-Ib/c can be produced by asymmetric explosions is supported by polarimetry observations of core-collapse SNe (e.g. Wang et al. 2001).

| SN 1998bw | $E_K (10^{52})_{\text{erg}}$ | $^{56}\text{Ni}(M_\odot)$ | $M_{\text{core}}(M_\odot)$ | $M_{\text{MS}}(M_\odot)$ | $M_{\text{left}}(M_\odot)$ | Ref. |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----|
| 2         | 0.7             | 12-15           | 40              | $\sim 2.9$     | Woosley et al. 1999 |
| 2         | 0.45            | 6-11            | 25-35           | $\sim 2$       | Nakamura et al. 2001 |
| 0.7-5     | 0.4             | 14              | 40              | $\sim 3$       |
Leonard et al. 2000), which seem to indicate that the degree of polarization increases along the SN-type sequence: II $\rightarrow$ Ib $\rightarrow$ Ic (i.e. with decreasing the envelope mass).

However, the association between two peculiar astrophysical objects such as GRB 980425 (very faint gamma-ray emission, unusual afterglow properties) and SN 1998bw (overluminous SN characterized by unusual spectroscopic features) was believed to be only suggestive, rather than representative, of the existence of a general SN/GRB connection.

2) The light curves of many afterglows show rebrightenings that have been interpreted as emerging supernovae outshining the afterglow several days or weeks after the GRB event (Bloom et al. 1999, Zeh, Klose & Hartmann 2004, and references therein). However, since other explanations such as dust echoes (Esin & Blandford 2000) or thermal re-emission of the afterglow light (Waxman & Draine 2000) could not be ruled out, only spectroscopic observations during the rebrightening phase could remove the ambiguity. Indeed spectroscopic features of SNe are unique, being characterized by FWHM $\sim$ 100 Å (see section 4).

3) The detection of star–formation features in the host galaxies of GRBs (Djorgovski et al. 1998, Fruchter et al. 1999) has independently corroborated the existence of a link with the death of massive stars. For example, Christensen, Hjorth & Gorosabel (2004) have found that GRB hosts are galaxies with a fairly high (relative to the local Universe) star formation of the order of $10 M_\odot$ yr$^{-1}$/L$^*$ (see also Le Floc’h et al. 2003). Also the location of GRBs within their host galaxies seems consistent with the regions that contain massive stars (Bloom, Kulkarni & Djorgovski 2002a).

4) Some GRB afterglows have shown absorption features at velocities of a few $\times 10^3$ km/s that has been interpreted as the result of the interaction with the stellar winds originating from the massive progenitors (Chevalier & Li 2000, Mirabal et al. 2003).

4. – SN 2002lt/GRB 021211

One of the first opportunities to carry out spectroscopic observations during a GRB afterglow rebrightening arrived in late 2002. GRB 021211 was detected by the HETE–2 satellite (Crew et al. 2003), allowing the localization of its optical afterglow (Fox et al. 2003) and the measurement of the redshift $z = 1.006$ (Vreeswijk et al. 2002). Fig. 3 shows the result of the late-time photometric follow-up, carried out with the ESO VLT–UT4 (Della Valle et al. 2003), together with observations collected from literature. A rebrightening is apparent, starting $\sim$ 15 days after the burst and reaching the maximum ($R \sim 24.5$) during the first week of January. For comparison, the host galaxy has a magnitude $R = 25.22 \pm 0.10$, as measured in late-time images. A spectrum of the afterglow + host obtained with FORS 2, 27 days after the GRB, during the rebrightening phase is shown in the rest frame of the GRB (red solid line). The spectrum of the bump is characterized by broad low-amplitude undulations blueward and redward of a broad absorption, the minimum of which is measured at $\sim 3770$ Å (in the rest frame of the GRB), whereas its blue wing extends up to $\sim 3650$ Å. The comparison with the spectra of SN 1994I, and to some extent also of SN 1991bg and SN 1984L (Fig. 2 in Della Valle et al. 2003) supports the identification of the broad absorption with a blend of the Ca II H and K absorption lines. The blueshifts corresponding to the minimum of the absorption and to the edge of the blue wing imply velocities $v \sim 14400$ km/s and $v \sim 23000$ km/s, respectively. The exact epoch when the SN exploded depends crucially on its rising time to maximum light. SN 1999ex, SN 1998bw and SN 1994I (the best documented examples
of type-Ic SNe) reached their $B$-band maximum $\sim 18$, 16 and 12 days after the explosion (Hamuy 2003). In Fig. 3 the light curve of SN 1994I (dereddened by $A_V = 2$ mag) is added to the afterglow and host contributions, after applying the appropriate $K$-correction (solid line). As it can be seen, this model reproduces well the shape of the observed light curve. A null time delay between the GRB and the SN explosions is required by our photometric data, even if a delay of a few days would also be acceptable given the uncertainties in the measurements. It is interesting to note that SN 1994I, the spectrum of which provides the best match to the observations, is a typical type-Ic event rather than a bright Hypernova as the ones proposed for association with other long duration GRBs (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004).

Fig. 3. – **Left panel.** Light curve of the afterglow of GRB 021211. Filled circles represent data from published works (Fox et al. 2003; Li et al. 2003; Pandey et al. 2003), open circles are converted from HST measurements (Fruchter et al. 2002), while filled diamonds indicate our data; the arrow shows the epoch of our spectroscopic measurement. The dotted and dot-dashed lines represent the afterglow and host contribution respectively. The dashed line shows the light curve of SN 1994I reported at $z = 1.006$ and dereddened with $A_V = 2$ (from Lee et al. 1995). The solid line shows the sum of the three contributions. **Right panel.** Spectrum of the afterglow+host galaxy of GRB 021211 (middle line), taken on Jan 8.27 UT (27 days after the burst). For comparison, the spectra of SN 1994I (type Ic, bottom) and SN 1991bg (peculiar type Ia, top) are displayed, both showing the Ca absorption. Plots from Della Valle et al. 2003, 2004.

5. – The “Smoking Gun”: GRB 030329/SN 2003dh

The peculiarity of the SN 1998bw/GRB 980425 association and the objective difficulties to collect data for SN 2002lt (4 h at VLT to get one single spectrum) prevented
us from generalizing the existence of a SN/GRB connection, although both cases were clearly suggestive. The breakthrough in the study of the GRB/SN association arrived with the bright GRB 030329. This burst, also discovered by the HETE-2 satellite, was found at a redshift $z = 0.1685$ (Greiner et al. 2003), relatively nearby, therefore allowing detailed photometric and spectroscopic studies. SN features were detected in the spectra of the afterglow by several groups (Stanek et al. 2003, Hjorth et al. 2003; see also Kawabata et al. 2003; Matheson et al. 2003a) and the associated SN (SN 2003dh) looked strikingly similar to SN 1998bw (Fig. 4). The gamma-ray and afterglow properties of this GRB were not unusual among GRBs, and therefore, the link between GRBs and SNe was eventually established to be general, so that, it applies to all “classical” and “long” cosmological GRBs.

The modeling of the early spectra of SN 2003dh (Mazzali et al. 2003) has shown that SN 2003dh had a high explosion kinetic energy, $\sim 4 \times 10^{52}$ erg (if spherical symmetry is assumed). However, the light curve derived from fitting the spectra suggests that SN 2003dh was not as bright as SN 1998bw, ejecting only $\sim 0.35 M_\odot$ of $^{56}$Ni. The progenitor was a massive envelope-stripped star of $\sim 35 - 40 M_\odot$ on the main sequence (Mazzali et al. 2003). The spectral analysis of the nebular-phase emission lines carried out by Kosugi et al. (2004) suggests that the explosion of the progenitor of the GRB 030329 was aspherical, and that the axis is well aligned with both the GRB relativistic jet and our line of sight.

6. – GRB 031203/SN 2003lw: the Older Brother of GRB 980425/SN 1998bw

GRB 031203 was a 30s burst detected by the INTEGRAL burst alert system (Mereghetti et al. 2003) on 2003 Dec 3. At $z = 0.1055$ (Prochaska et al. 2004), it was the second
Table II. – Hypernovae

| SN    | ez (km/s) | References               |
|-------|-----------|--------------------------|
| 1997dq| 958       | Mazzali et al. 2004      |
| 1997ef| 3539      | Filippenko 1997b         |
| 1998bw| 2550      | Galama et al. 1998       |
| 1999as| 36000     | Hatano et al. 2001       |
| 2002ap| 632       | Mazzali et al. 2002, Foley et al. 2003 |
| 2002bl| 4757      | Filippenko et al. 2002   |
| 2003bg| 1320      | Filippenko & Chornack 2003 |
| 2003dh| 46000     | Stanek et al. 2003, Hjorth et al. 2003 |
| 2003jd| 5635      | Filippenko et al.2003; Matheson et al. 2003b |
| 2003lw| 30000     | Malesani et al. 2004     |
| 2004bu| 5549      | Foley et al. 2004        |

closest burst after GRB 980425. The burst energy was extremely low, of the order of \(10^{49}\) erg, well below the “standard” reservoir \( \sim 10^{51}\) erg of normal GRBs (Frail et al. 2001, Panaitescu & Kumar 2001). Only GRB 980425 and XRF 020903 were less energetic. In this case, a very faint NIR afterglow could be discovered, orders of magnitude dimmer than usual GRB afterglows (Malesani et al. 2004). A few days after the GRB, a rebrightening was apparent in all optical bands (Bersier et al. 2004; Thomsen et al. 2004; Cobb et al. 2004; Gal-Yam et al. 2004). The rebrightening amounted to \( \sim 30\%\) of the total flux (which is dominated by the host galaxy), and was coincident with the center of the host galaxy to within 0.1′′ (\(\sim 200\) pc). For comparison, in Fig. 5 the VRI light curves of SN 1998bw are plotted (solid lines; from Galama et al. 1998), placed at \(z = 0.1055\) and dereddened with \(E_{B-V} = 1.1\). Even after correcting for cosmological time dilation, the light curve of SN 2003lw is broader than that of SN 1998bw, and the latter requires an additional stretching factor of \( \approx 1.1\) to match the \(R\) and \(I\) data points. The \(R\)-band maximum was reached in \(\sim 18\) (comoving) days after the GRB. After assuming a light curve shape similar to SN 1998bw, which had a rise time of 16 days in the \(V\) band, data suggest an explosion time nearly simultaneous with the GRB. A precise determination of the absolute magnitude of the SN is made difficult by the uncertain extinction. Based on the ratios of the Balmer lines of the host galaxy, the average combined Galactic and host extinction is \(E_{B-V} \approx 1.1\). Given the good spatial coincidence of the SN with the center of the host, such value is a good estimate for the SN extinction. With the assumed reddening, SN 2003lw appears to be brighter than SN 1998bw by 0.5 mag in the \(V\), \(R\), and \(I\) bands. The absolute magnitudes of SN 2003lw are hence \(M_V = -19.75 \pm 0.15\), \(M_R = -19.9 \pm 0.08\), and \(M_I = -19.80 \pm 0.12\). Fig. 5 also shows the spectra of the rebrightening on 2003 Dec 20 and Dec 30 (14 and 23 rest-frame days after the GRB), after subtracting the spectrum taken on Mar 1 (81 rest-frame days after the GRB, Tagliaferri et al. 2004). The spectra of SN 2003lw are remarkably similar to those of SN 1998bw obtained at comparable epochs (shown as dotted lines in Fig. 5, see Malesani et al. 2004 for details). Both SNe show very broad absorption features, indicating high expansion velocities. This makes SN 2003lw another example of Hypernova. A preliminary analysis of early spectra of 2003lw (Mazzali et al. 2005, in preparation) indicates that this Hypernova produced a large amount of Ni, possibly in the range \(0.6 - 0.9 M_\odot\). The progenitor mass could be as large as 40-50 \(M_\odot\) on the main sequence.
Fig. 5. **Left panel.** Optical and NIR light curves of GRB 031203 (circles). The solid curves show the evolution of SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999), rescaled at $z = 0.1055$, stretched by a factor 1.1, extinguished with $E(B-V) = 1.1$, and brightened by 0.5 mag. The dashed lines indicate the host galaxy contribution. The vertical dotted lines mark the epochs of our spectra. **Right panel.** Spectra of SN 2003lw, taken on 2003 December 20 and 30 (solid lines), smoothed with a boxcar filter 250 Å wide. Dotted lines show the spectra of SN 1998bw (from Patat et al. 2001), taken on 1998 May 9 and 19 (13.5 and 23.5 days after the GRB, or 2 days before and 7 days after the $V$-band maximum, respectively), extinguished with $E(B-V) = 1.1$ and a Galactic extinction law (Cardelli et al. 1989). The spectra of SN 1998bw were vertically displaced for presentation purposes. Plots from Malesani et al. 2004.

7. Rates of SNe Ib/c, Hypernovae and GRBs

The measurement of the SN rate is based on the control-time methodology (Zwicky 1938) that implies the systematic monitoring of galaxies of known distances and the use of appropriate templates for the light curves of each SN type (see Cappellaro et al. 1993 for bias and uncertainties connected with this procedure). Unfortunately all Hypernovae reported in Tab. II have been not discovered during time ‘controlled’ surveys, and therefore any attempt to derive an absolute value of the rate of Hypernovae should be taken with great caution. One possibility is to compute the frequency of occurrence of all SNe-Ib/c and Hypernovae in a limited distance sample of objects. From the Asiago catalogue (http://web.pd.astro.it/supern) we have extracted 91 SNe-Ib/c, 8 of which are Hypernovae, with $cz < 6000$ km/s. This velocity threshold is suitable to make the distance distribution of ‘normal’ Ib/c and Hypernovae statistically indistinguishable (KS probability=0.42, see Fig. 6). After assuming that the host galaxies of both ‘normal’ SNe Ib/c and Hypernovae have been efficiently (or inefficiently) monitored by the same extent, one can infer that the fraction of Hypernovae is about $7/91 \approx 8\%$ (after excluding SN 1998bw because it was searched in the error-box of GRB 980425) of the total number.
Fig. 6. – Cumulative distribution for SNe Ib/c (solid line) and Hypernovae (dashed line) discovered in galaxies with radial velocities $cz < 6000$ km/s.

of SNe Ib/c. Since Hypernovae can be brighter than normal SNe-Ib/c, their discovery may be favored, therefore 8% should be regarded as an upper limit for their frequency of occurrence. For a “Milky-Way–like” galaxy (i.e. $L_B = 2.3 \times 10^{10} L_{B,\odot}$; $M = 9.5 \times 10^{10} M_{\odot}$; and morphological Hubble type Sbc, data from Cox 2000) we obtain a rate of type Ib/c SNe of $\sim 3.2 \times 10^{-3}$ yr$^{-1}$ (after assuming a rate of 0.14 SNe per century and per $10^{10} L_{B,\odot}$; Cappellaro, Evans & Turatto 1999), and therefore the Hypernova rate turns out to be $\sim 2.6 \times 10^{-4}$ yr$^{-1}$. This rate has to be compared with the rate of GRBs in the Milky Way. This quantity can be estimated by combining the local rate of 0.5 GRB event Gpc$^{-3}$ yr$^{-1}$ (Schmidt 2001), the local density of B luminosity of $\sim 1.2 \times 10^8 L_{B,\odot}$ per Mpc$^3$ (e.g. Madau, Della Valle & Panagia 1998) and the B luminosity of the Milky Way ($2.3 \times 10^{10} L_{B,\odot}$). This approach gives $R_{GRB} \sim 3.8 \times 10^{-7}$ yr$^{-1}$ that has to be rescaled for the beaming factor $f_b^{-1}$. There exist different estimates for this parameter: from $\sim 500$ (Frail et al. 2001) to $\sim 75$ (Guetta, Piran & Waxman 2005, Piran 2005). These figures implies that the ratio GRB/Hypernovae spans the range $\sim 0.7 \div 0.11$. Following Mannucci et al. (2005), who provide the SN rates normalized to the mass in stars of the host galaxies, the same kind of computation yields a ratio GRB/Hypernovae of $\sim 0.20 \div 0.03$. These data as a whole do not support a ratio GRB/Hypernova=1, unless to assume large values of $f_b^{-1}$ (e.g. Frail et al. 2001, Yonetoku et al. 2005). A piece of evidence in this direction comes from observations of the radio properties exhibited by SN 2002ap (Berger, Kulkarni & Chevalier 2002) that do not support the association of this Hypernova with a GRB. For $f_b^{-1} \sim 50 \div 100$ (Guetta et al. 2004, Piran 2005) the ratio GRB/Hypernova should be of the order of $\sim 0.1$ (or even less). Incidentally we note that the ratio GRBs/SNe-Ibc $\sim 0.05 \div 0.008$ (which can be obtained from the rates reported above) is consistent with the results independently obtained by Berger et
Table III. – Supernova-Gamma Ray Burst time lag. A negative time lag indicates that the SN explosion precedes the GRB.

| GRB      | SN     | $\Delta t$(days) | $-\Delta t$(days) | References            |
|----------|--------|------------------|-------------------|-----------------------|
| GRB 980425 | 1998bw | 0.7              | -2                | Iwamoto et al. 1998   |
| GRB 000911 | bump   | 1.5              | -7                | Lazzati et al. 2001   |
| GRB 011121 | 2001ke | 0                | -5                | Bloom et al. 2002b    |
|           |        |                  | a few             | Garnavich et al. 2003 |
| GRB 021211 | 2002lt | 1.5              | -3                | Della Valle et al. 2003 |
| GRB 030329 | 2003dh | 2                | -8                | Kawabata et al. 2003  |
| GRB 031203 | 2003lw | 0                | -2                | Matheson et al. 2003  |

al. 2003 (see also Soderberg 2005), who derived, from radio observations of 33 ‘local’ SNe-Ib/c, an incidence of 1998bw-like events over the total number of SNe-Ibc of $< 0.03$ (see also Granot & Ramirez-Ruiz 2004).

8. – SN-GRB time lag

Several authors have reported the detection of Fe and other metal lines in GRB X-ray afterglows (e.g. Piro et al. 1999; Antonelli et al. 2000; Reeves et al. 2002). If valid (see Sako et al. 2005 for a critical view) these observations would have broad implications for both GRB emission models and would strongly link GRBs with SN explosions. For example, Butler et al. (2003) have reported the detection in a Chandra spectrum of emission lines whose intensity and blueshift would imply that a supernova occurred $> 2$ months prior to the $\gamma$ event. This kind of observations can be accommodated in the framework of the 

9. – . . . There is an Expanding Frontier of Ignorance . . . (R. Feynman, Six Easy Pieces)

Data presented in previous sections provide robust empirical grounds to the idea that some types of core-collapse SNe are the progenitors of long-duration GRBs (see also Dar 2004, Matheson 2005, Stanek 2005). On the other hand, the existence of SN/GRB associations poses intriguing questions which have not yet been answered.

1. What kind of SNe are connected with long-duration GRBs and XRFs?

Evidence based on the associations between SN 1998bw/GRB 980425, SN 2003dh/GRB 030329, and SN 2003lw/GRB 031203 would suggest that the parent SN population of GRBs is formed by the bright tail of Hypernovae. However, there is growing evidence that other types of SNe-Ib/c, such as ‘standard’ Ic events like SN 1994I or faint Hypernovae can contribute to produce GRBs/XRFs (Della Valle et al. 2003; Fynbo et al. 2004, Fig. 7; Tominaga et al. 2004; Levan et al. 2005a, Fig. 8; Masetti et al. 2003, Price et al.
2003a, Price et al. 2003b, Soderberg et al. 2005, Gorosabel et al. 2005). Available data suggest the existence of $\sim 5$ mag spread ($M_V \sim -16 \div -21$) in the absolute magnitudes at maximum of SNe-Ib/c associated with GRBs/XRFs, which may be similar to the magnitude spread exhibited by local SNe-Ib/c (see Fig. 11 in Soderberg et al. 2005).

Possible associations between GRBs and other types of core-collapse SNe (particularly with type IIn) have been claimed in the past on the basis of spatial and temporal SN/GRB coincidences by Germany et al. (2000) and Turatto et al. (2000) (SN 1997cy/GRB 970514) and by Rigon et al. (2003) (SN 1999E/GRB 980910). However, in a recent study, Valenti et al. (2005) were not able to confirm these associations to be statistically significant (see also Wang & Wheeler 1998; Kippen et al. 1998). Currently the best evidence for the case of an association between a Supernova IIn and a gamma ray burst has been provided by Garnavich et al. (2003) who find that the color evolution of the bump associated with GRB 011121 is consistent with the color evolution of an underlying SN (dubbed as SN 2001ke) strongly interacting with a dense circumstellar gas due to the progenitor wind (as confirmed by radio observations, see Price et al. 2002).

**Fig. 7.** – The light curve of the bump associated with XRF 030723 compared with the B light curve of the ‘standard’ (type-Ic) SN 1994I redshifted to $z = 0.6$ (data from Richmond et al. 1996). Plot from Fynbo et al. 2004.

2. **What are the most frequent gamma-ray events in the Universe?**

GRB 031203 was quite similar to GRB 980425, albeit more powerful. Both events consisted in a single, under-energetic pulse. Their afterglows were very faint or absent in the optical, and showed a very slow decline in the X rays. Moreover, they were both accompanied by a powerful Hypernova. Therefore, GRB 980425 can no longer be considered as a peculiar, atypical case. Both bursts were so faint, that they would have been easily missed at cosmological distances. Since the volume they sample is $10^3 \div 10^6$ times smaller than that probed by classical distant GRBs, the rate of these events could be dramatically larger, perhaps they are the most common GRBs in the Universe. However we are still left with the question of whether or not these bursts belong to a different local
population of γ-bursts (Bloom et al. 1998, Soderberg, Frail & Wiering 2004) or they are typical cosmological bursts observed off-axis (Nakamura 1999; Eichler & Levinson 1999; Woosley et al. 1999; Ramirez-Ruiz et al. 2004; see also Waxman 2004 for a pro and con discussion). Naively one may expect that the spectroscopic and photometric similarities exhibited by SNe 1998bw, 2003dh and 2003lw may indicate a common origin for the associated GRBs, in spite of the fact that they have exhibited dramatic differences in their γ-energy budgets and in the properties of their afterglows. We note that this inference is supported by statistical arguments provided by Guetta et al. (2004).

3. What is the relationship between the SN magnitudes at maximum light and the gamma-ray energy budget?

Simple statistical analysis of data points reported in Fig. 9 shows that the absolute magnitude at maximum of SNe associated with GRBs does not appear to correlate with the respective gamma energy (although this conclusion should be taken with caution because of the usage of scanty statistic). The distribution of the data points in Fig. 9 also reflects an obvious bias, namely the detection of over-bright SNe is favored because most GRBs are discovered at cosmological distances and/or their bright afterglows can easily outshine ‘standard’ SNe-Ib/c or faint Hypernovae. However it is not clear if the lack of faint SNe associated with intrinsically faint (and nearby) GRBs is the result of an exiguous statistic or this finding has a deeper physical meaning.

4. May it be that GRBs, which occur in the inner and outer regions of hosts, have different progenitors?

Ramirez-Ruiz, Lazzati & Blain (2002) found some evidence that outer bursts appear to have systematically greater isotropic equivalent energies (or narrower jets). These
results may be interpreted in terms of different environmental properties, between inner and outer regions of the hosts (e.g. metallicity, fraction of binary systems), which can affect the evolution of the progenitors of core-collapse SNe (see Bressan, Della Valle & Marziani 2002 for a discussion).

5. Are the “red bumps” always representative of the signatures of incipient SNe?

Or can some of them be produced by different phenomena such as dust echoes (Esin & Blandford 2000) or thermal re-emission of the afterglow light (Waxman & Draine 2000). To date, only for GRB 021211/SN 2002lt (Della Valle et al. 2003) and XRF 020903 (Soderberg et al. 2005) a spectroscopic confirmation was obtained. On the other hand, Garnavich et al. (2003) and Fynbo et al. (2004) did not find SN (spectroscopic) features in the bumps of GRB 011121 and XRF 030723 (see Butler et al. 2005 for an alternative interpretation of the bump discovered in XRF 030723).

6. Is the lack of an optical bump indicative of the lack of a supernova?

Price et al. (2003b), Levan et al. (2005b), Soderberg et al. (2005) have carried out unsuccessful HST searches for SN signatures in GRBs/XRFs light curves. For example Soderberg et al. (2005) were able to set a firm upper limit to the magnitude of the SN
associated with XRF 040701, of $M_V \lesssim -16.2$ (see the faintest upper limit in Fig. 9). This behaviour can be explained in a number of ways: i) the SN parent population of GRBs/XRFs is formed by a heterogeneous class of objects that span (at maximum light) a broad range of luminosities (about a factor 100); ii) some ‘long’ GRBs may originate by merging compact objects (e.g. Belczynski, Bulik & Rudak 2002; Della Valle, Marziani & Panagia 2005) rather than in SN explosions; iii) sometimes SN and GRB do not occur simultaneously (e.g. Vietri & Stella 1998). For a delay of a few weeks/months, the supernova would have faded before the GRB was detected, and this may explain why supernovae are not discovered after every GRB. Finally we note that the light curve of the afterglow of GRB 030329 (associated with SN 2003dh) did not show the bump which is believed to be caused by the emerging SN (Matheson et al. 2003a their Fig. 13, Lipkin et al. 2004).

7. What causes some small fraction of SNe Ib/c to produce observable GRBs, while the majority do not?

With the obvious exceptions of SN 1998bw, 2003dh and 2003lw, none of the Hypernovae reported in Tab. II have been associated with GRBs by direct observations (the association GRB 971115/SN 1997ef, for example, has been proposed by Wang & Wheeler (1998) on the basis of spatial and temporal coincidences). The situation is even more intriguing if one considers that Hypernovae are only a small fraction of ‘normal’ SNe-Ibc (less than 10%) and thus only a very tiny fraction of SNe-Ib/c, about 0.8% ± 5%, seems to be able to produce GRBs. This may imply that the evolution leading a star to produce a GRB requires very special circumstances (e.g. rotation, binary interaction; see Podsiadlowski et al. 2004, Mirabel 2004, Fryer & Heger 2005) other than being ‘only’ a very massive star. As an alternative, one can argue that most SNe Ib/c (if not all of them) produce GRBs (Lamb, Donaghy & Graziani 2005). This fact would imply very small jet opening angles (~ 1 degree) and therefore one should be able to detect as GRBs only those events which are viewed at very small angles relative to the jet direction. More spherically symmetric jets or events viewed from angles (relative to the jet direction) which are larger than the typical viewing angles of long-duration GRBs, should yield XRFs (see also Dado, Dar & De Rjula 2004). Finally, at even larger angles, relative to the jet direction, one should observe ‘only’ the SN(Ib/c) explosions. With a rate of discovery of about 2 event/week, the Swift satellite (Gehrels et al. 2004) will allow the GRB community to obtain in the next 3 ± 4 years an accurate spectroscopic classification for dozens SNe associated with GRBs and to provide conclusive answers to several of the above questions.

* * *

It is a pleasure to thank N. Panagia and D. Malesani for their useful comments and the critical reading of the manuscript. I’m also indebted with S. Benetti, G. Chincarini, F. Frontera, N. Gehrels, K. Hurley, P. Mazzali, L. Stella, G. Tagliaferri and V. Trimble for suggestions and illuminating discussions and with M. Hamuy, K. Stanek, A. Levan, J. Fynbo and F. Patat to have made available their plots.

REFERENCES
Antonelli, L. A., Piro, L., Vietri, M. et al. 2000, ApJ, 545, L39
Baade, W. & Zwicky, F. 1934a, Proc. Natl. Acad. Sci. USA, 20, 254+259
Barbon, R., Ciatti, F., Rosino, L. 1979, A&A, 72, 287
Belczynski, K., Bulik, T., Rudak, B. 2002, ApJ, 571, 394
Benetti, S., Cappellaro, E., Danziger, I. J., Turatto, M., Patat, F., Della Valle, M. 1998, MNRAS, 294, 448
Benetti, S., Turatto, M., Cappellaro, E., Danziger, I. J., Mazzali, P. 1999, MNRAS, 305, 811
Berger, E., Kulkarni, S. R., Chevalier, R.A. 2002, ApJ, 577, L5
Berger, E., Kulkarni, S. R., Frail, D. A., Soderberg, A. M. 2003, ApJ, 599, 408
Bersier, D., Rhoads, J., Fruchter, A., et al. 2004, GCN Circ. 2544
Bertola, F. 1964, Ann. Astroph, 27, 319
Bloom, J. S., Kulkarni, S. R., Prince, T., Phinney, E. S., Frail, D. A. 1998, ApJ, 506, L105
Bloom, J. S., Kulkarni, S. R., Djorgovski, S. G. et al. 1999, Nature, 401, 453
Bloom, J. S., Kulkarni, S. R., Djorgovski, S. G. 2002a, AJ, 123, 1111
Bloom, J. S.; Kulkarni, S. R.; Price, P. A. et al. 2002b, ApJ, 572, L45
Branch, D., Benetti, S., Kasen, D. et al. 2002, ApJ, 566, 1005
Bressan, A., Della Valle, M., Marziani, P. 2002, MNRAS, 331, L25
Butler, N.R., Marshall, H.L., Ricker, G.R., Vanderspek, R.K., Ford, P.G., Crew, G. B., Lamb, D.Q., Jernigan, J.G. 2003, ApJ, 597, 1010
Butler, N.R., Sakamoto, T., Suzuki, M. et al. 2005, ApJ, submitted, astro-ph/0408453
Cappellaro, E., Turatto, M., Benetti, S., Tsvetkov, D. Y., Dartunov, O. S., Makarova, I. N. 1993, A&A, 268, 472
Cappellaro, E., Evans, R., Turatto, M. 1999, A&A, 351, 459
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chevalier, R.A., Li, Z. 2000, ApJ, 536, 195
Christensen, L., Hjorth, J., Gorosabel, J. 2004, A&A, 425, 913
Chugai, N. 1997, ARep, 41, 672
Clocchiatti, A., Wheeler, J. C. Brotherton, M. et al. 1996, ApJ, 459, 547
Clocchiatti, A.; Wheeler, J. C. 1997, ApJ, 491, 375
Clocchiatti, A., Suntzeff, N.B., Phillips, M.M. et al. 2001, ApJ, 553, 886
Cobb, B. E., Baylin, C. D., van Dokkum, P. G., Buxton, M. M. & Bloom, J. S. 2004, ApJ, 608, L93
Colgate, S. 1968, Can. J. Phys., 46, 476
Costa, E., Frontera, F., Heise, J., et al. 1997, Nature, 387, 783
Cox, A.N. 2000, in Allen’s astrophysical quantities, 4th ed. Publisher: New York: AIP Press; Springer, 2000
Crew, G. B., Lamb, D. Q., Ricker, G. R., et al. 2003, ApJ, 599, 387
Dado, S., Dar, A., De Rjula, A. 2004, A&A, 422, 381
Dar, A. 2004, Astrophysics Workshop, Vulcano, Italy, May 24-29, 2004; astro-ph/0405386
Della Valle M., Malesani, D., Benetti, S. et al. 2003, A&A, 406, L33
Della Valle M., Malesani, D., Benetti, S. et al. 2004, in the Proceedings of the 2003 GRB Conference (Santa Fe, 2003 Sep 8-12), eds. Fenimore, E., Galassi, M., p. 403
Della Valle, M. Marziani, P., Panagia, N. 2005, this Conference
Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., Goodrich, R., Frail, D. A., Piro, L.; Palazzi, E. 1998, ApJ, 508, L17
Doggett, J. B., Branch, D. 1985, AJ, 90, 2303
Elias, J. H., Matthews, K., Neugebauer, G., Persson, S. E. 1985, ApJ, 296, 379
Eichler, D., Levinson, A. 1999, ApJ, 521, L117
Esin, A. & Blandford, R. 2000, ApJ, 534, L151
Filippenko, A.V. 1988, AJ, 96, 1941
Filippenko, A.V., Matheson, T., Ho, L. C. 1993, ApJ, 415, L103
Filippenko, A.V., Barth, A.J., Matheson, T. et al. 1995, ApJ, 450, L11
Filippenko, A.V. 1997a, ARA&A, 35, 309
Filippenko, A.V. 1997b, IAUC, n. 6783
Filippenko, A.V. 1998, IAUC, 6969
Filippenko, A.V., Leonard, D.C., Moran, E.C. 2002, IAUC, n. 7845
Filippenko, A.V. & Chornock, R. 2003, IAUC, n. 8084
Filippenko, A.V., Foley, R.T., Swift, B. 2003, IAUC, n. 8234
Foley, R.J., Wong, D.S., Moore, M. & Filippenko, A.V. 2004, IAUC, n. 8353
Foley, R.J., Papenkova, M.S., Swift, B. J. et al. 2003, PASP, 115, 1220
Fox, D. W., Price, P. A., Soderberg, A. M., et al. 2003, ApJ, 586, L5
Frail, D.A., Kulkarni, S.R., Nicastro, S.R. et al. 1997, Nature, 389, 261
Frail, D. A., Kulkarni, S. R., Sari, R. et al. 2001, ApJ, 562, L55
Fruchter, A.S., Thorsett, S. E., Metzger, M.R. et al. 1999, ApJ, 519, L13
Fruchter, A. S., Levan, A., Vreeswijk, P. M., Holland, S. T. & Kouveliotou, C. 2002, GCN Circ, 1781
Fryer, C.L., Heger, A. 2005, ApJ, submitted, astro-ph/041224
Fynbo, J., Sollerman, J., Hjorth, J. et al. 2004, ApJ, 609, 962
Gal-Yam, A., Ofek, E.O., Shemmer, O. 2002, MNRAS, 332, L73
Gal-Yam, A., Moon, D.S., Fox, D.B. et al. 2004, ApJ, 609, L59
Galama, T.J., Vreeswijk, P. M., van Paradijs, J., et al. 1998, Nature, 395, 670
Garavich, P. M., Stanek, K. Z., Wyrzykowski, L. et al. 2003, ApJ, 582, 924
Garavich, P., Jha, S., Kirshner, R., Challis, P., Balam, D., Berlind, P., Thorstensen, J., Macri, L. 1997a, IAUC, n. 6798
Garavich, P., Jha, S., Kirshner, R., Challis, P., Balam, D., Brown, W., Briceno, C. 1997b, IAUC, n. 6786
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Germany L., Reiss, D. J. Sadler, E.M., Schmidt, B.P. Stubbs, C. W. 2000, ApJ, 533, 320
Ghirlanda, G., Ghisellini, G., Lazzati, D. 2004, ApJ, 616, 331
Gorosabel, J. et al. 2005, A&A, in press, astro-ph/0504050
Granot, J., Ramirez-Ruiz, E. 2004, ApJ, 609, L9
Greiner et al. 2003, GCN 2020
Guetta, D., Piran, T., Waxman, E. 2005, ApJ, 619, 412
Hamuy, M., Maza, Jos, Pinto, P. A. 2002, AJ, 124, 417
Hamuy, M. 2003, in “Core Collapse of Massive Stars”, ed. C.L. Fryer, Kluwer, Dordrecht; astro-ph/0301006
Harkness, R.P., Wheeler, J.C., Margon, B. et al. 1987, ApJ, 317, 355
Hatano, K., Branch, D., Nomoto, K., Deng J.S., Maeda, K., Nugent P., Aldering, G. 2001, 19tht BAAS, 33, p. 838
Hjorth J., Sollerman, J., Moller, P. et al. 2003, Nature,423, 847
Höflich, P.; Wheeler, J. C.; Wang, L. 1999, ApJ, 521, 179
Iben, I., Renzini, A. 1983, ARA&A, 21, 271
Iwamoto, K., Mazzali, P.A., Nomoto, K., et al. 1998, Nature, 395, 672
Iwamoto, K., Nakamura, T., Nomoto, K. et al. 2000, ApJ, 534, 660
Kawabata, K. S., Deng, J., Wang, L. et al. 2003, ApJ, 593, L19
Kippen, R. M., Briggs, M. S., Kommers, J. M., et al. 1998, ApJ, 506, L27
Klebesadel, R.W., Strong, I.B., Olson, R. A. 1973, ApJ, 182, L85
Kouveliotou, C. et al. 1993, ApJ, 413, L101
Kosugi, G. Mizumoto, Y. Kawai, N. et al. 2004, PASJ, 56, 61
Kulkarni, S. R., Fraile, D. A., Wieringa, M. H. et al. 1998, Nature, 395, 663
Lamb, D. Q., Donaghy, T. Q., Graziani, C. 2005, ApJ, 620, 355
Lazzati, D., Covino, S., Ghisellini, G. et al. 2001, A&A, 378, 996
Le Floc’h, E., Duc, P.-A., Mirabel, I. F. et al. 2003, A&A, 400, 499
Leonard, D.C., Filippenko, A.V., Barth, A.J.& Matheson, T. 2000, ApJ, 536, 239
Levan, A., Nugent, P., Fruchter, A. et al. 2005a, ApJ, in press, astro-ph/0403450
Levan, A., Patel, S., Kouveliotou, C. et al. 2005b, ApJ, 622, 977
Lee, M.G.; Kim, E. Kim, S.C.; Kim, S. L.; Park, W.; Pyo, T.S. 1995, JKAS, 28, 31L
Li, W., Filippenko, A. V., Chornock, R. & Jha, S. 2003, ApJ, 586, L9
Lipkin, Y. M., Ofek, E. O., Gal-Yam, A., et al. 2004, ApJ, 606, 381
Livio, M. 2001, in "Cosmic Evolution", Paris (November 2000), eds. E.Vangioni-Flam, R. Ferlet, and M. Lemoine. Published by New Jersey: World Scientific, 2001, pg. 299
MacFadyen, A. I., Woosley, S.E. 1999, ApJ, 524, 262
Madau, P., Della Valle, M., Panagia, N. 1998, MNRAS, 297, L17
Maeda, K., Nakamura, T., Nomoto, K., Mazzali, P., Patat, F., Hachisu, I. 2002, ApJ, 565, 405
Malesani D. Tagliaferri, G., Chincarini, G. et al.2004, ApJ, 609 L5
Mannucci, F., Della Valle, M., Panagia, N., Cappellaro, E., Cresci, G., Maiolino, R., Petrosian, A., Turatto, M. 2005, A&A, 433, 807
Masetti, N., Palazzi, E., Pian, E. et al. 2003, A&A, 404, 465
Matheson, T., Filippenko, A.V., Li, Weidong, Leonard, D.C., Shields, J. C. 2001, AJ, 12, 1648
Matheson, T.; Garnavich, P. M.; Stanek, K. Z. et al. 2003a, ApJ, 599, 394
Matheson, T., Challis, P. & Kirshner, R. 2003b, IAUC, n. 8234
Matheson, T. 2005, in the proceedings of "Supernovae as Cosmological Lighthouses", Padua, 2004, ASP conference Series: astro-ph/0410668
Maund, J.R., Smartt, S.J., Kudritzki, R. P., Podsiadlowski, P. Gilmore, G. F. 2004, Nature, 427, 129
Mazzali, P., Deng, J., Maeda, K., et al., 2002, ApJ, 572, L61
Mazzali, P., Deng, J., Tomimaga, N. et al. 2003, ApJ, 599, L95
Mazzali, P. A., Deng, J., Maeda, K., Nomoto, K., Filippenko, A. V., Matheson, T. 2004, ApJ, 614, 858
McKenzie, E.H., Schaefer, B. E. 1999, PASP, 111, 964
Mereghetti, S., & G¨ otz, D. 2003, GCN Circ. 2460
Metzger, M.R., Djorgovski, S.G., Kulkarni, S. R. et al. 1997, Nature, 387, 878
Minkowski, R. 1941, PASP, 53, 224
Mirabal, N., Halpern, J. P., Chornock, R., Filippenko, A.V., Terndrup, D. M., Armstrong, E., Kemp, J., Thorstensen, J. R., Tavarez, M., Espaillat, C. 2003, ApJ, 595, 935
Mirabel, I. F. 2004, RmxAC, 20, 14
Nakamura, T. 1999, ApJ, 522, L101
Nakamura, T., Mazzali, P., Nomoto, K., Iwamoto, K. 2001, ApJ, 550, 991
Nomoto, K., Mazzali, P.A., Nakamura, T., Iwamoto, K., Danziger, I. J., Patat, F. 2001, in “Supernovae and gamma-ray bursts: the greatest explosions since the Big Bang”, May, 1999, eds. M. Livio, N. Panagia, & K. Sahu. STScI symposium series, Vol. 13, pg 144
Paczynski, B. 1998, ApJ, 494, L45
Panagia, N. 1985, in “Supernovae as Distance Indicators”, Cambridge, MA, September, 1984, ed. Bartel, N.; Lect. Notes Phys. Vol. 224. Berlin Springer-Verlag. p. 14
Panaiteescu, A., Kumar, P. 2001, ApJ, 560, L49
Pandey, S.B., Anupama, G.C., Sagar, R., Bhattacharya, D., Castro-Tirado, A.J., Sahu, D.K., Parihar, P., Prabhu, T.P. 2003, A&A, 408, L21
Patat, F., Barbon, R., Cappellaro, E., Turatto, M. 1994, A&A, 282, 731
Patat, F., Cappellaro, E., Danziger, I.J., et al. 2001, ApJ, 555, 900
Piro, L., Costa, E., Feroci, M. et al. 1999, ApJ, 514, L73
Piran, T. 2005, this Conference
Podsiadlowski, P., Mazzali, P., Nomoto, K., Lazzati, D., Cappellaro, E. 2004, ApJ, 607, L17
Porter, A.C., Filippenko, A.V. 1987, AJ, 93, 1372
Price, P. A., Berger, E., Reichart, D. E., et al. 2002, ApJ, 572, L51
Price, P. A., Kulkarni, S. R., Berger, E., et al. 2003a, ApJ, 589, 838
Price, P.A., Kulkarni, S.R., Schmidt, B.P. et al. 2003b, ApJ, 584, 931
Prochaska, J.X., Bloom, J. S., Chen, H., Hurley, K. C., Melbourne, J., Dressler, A., Graham, J.R., Osip, D. J., Vacca, W. D. 2004, ApJ, 611, 200
Ramirez-Ruiz, E., Lazzati, D., Blain, A. W. 2002, ApJ, 565, L9
Ramirez-Ruiz, E., Granot, J., Kouveliotou, C., Woosley, S.E., Patel, S. K, Mazzali, P. 2004, ApJ, submitted, astro-ph/0412145

Reeves, J. N., Watson, D., Osborne, J. P. et al. 2002, Nature, 416, 512
Richmond, M. W., Van Dyk, S. D., Ho, W., et al. 1996, AJ, 111, 327
Rigon, L., Turatto, M., Benetti, S., Pastorello, A., Cappellaro, E., Aretxaga, I., Vega, O.,
Chavushyan, V., Patat, F., Danziger, I. J. Salvo, M. 2003, MNRAS, 340, 191
Ruffini, R., Bianco, C.L., Fraschetti, F., Xue, S., Chardonne, P. 2001, ApJ, 555, L117
Sak0, M., Harrison, F., Rutledge, R. 2005, ApJ, in press, astro-ph/0406210
Schlegel, E.M. 1990, MNRAS, 244, 269
Schmidt, M. 2001, ApJ, 552, 36
Soderberg, A. M., Frail, D. A., Wieringa, M. H. 2004, ApJ, 607, L13
Soderberg, A. M. 2005, this Conference
Soderberg, A.M., Kulkarni, S.R., Fox, D.B. et al. 2005, ApJ, submitted, astro-ph/0502553
Sollerman, J., Kozma, C., Fransson, C., Leibundgut, B., Lundqvist, P., Ryde, F., & Woudt, P. 2000, ApJ, 537, L127
Stanek, K. Z., Matheson, T., Garnavich, P. M. et al. 2003, ApJ, 591, L17
Stanek, K.Z. 2005, in First International Workshop on “Stellar Astrophysics with the World Largest Telescopes”, Torun, Poland, 7-10 September 2004, astro-ph/0411361
Stanek, K.Z., Garnavich, P.M., Nutzman, P.A., Hartman, J. D., Garg, A. 2005, ApJL submitted, astro-ph/0502319
Stathakis, R. A., Boyle, B. J., Jones, D. H. et al. 2000, MNRAS, 314, 807
Stritzinger, M., Hamuy, M., Suntzeff, Nicholas B. et al. 2002, AJ, 124, 2100
Swartz, D. A., Clocchiatti, A., Benjamin, R.; Lester, D. F., Wheeler, J. C. 1993, Nature, 365, 232
Tagliaferri, G., Covino, S. & Fugazza, D., et al. 2004, IAU Circ. 8308
Thomsen, B., Hjorth, J., Watson, D. et al. 2004, A&A, 419, L21
Tomimaga, N., Deng, J., Mazzali, P., Maeda, K., Nomoto, K., Pian, E., Hjorth, J., Fynbo, J. 2004, ApJ, 612, L105
Turatto, M., Mazzali, P., Young, T.R. et al. 1998, ApJ, 498, L129
Turatto M., Suzuki, T., Mazzali, P., Benetti, S., Cappellaro, E., Danziger, I.J., Nomoto, K., Nakamura, T., Young, T.R., Patat, F. 2000, 534 L57
Uomoto, A., Kirshner, R. P. 1985, A&A, 149, L7
Valenti, S., Cappellaro, E., Della Valle, M., Frontera, F., Guidorzi, C., Montanari, E. 2005, this Conference
van Paradijs, J., Groot, P.J., Galama, T., et al. 1997, Nature, 386, 686
Vietri, M. & Stella, L. 1998, ApJ, 507, L45
Vreeswijk, P. M., Fruchter, A., Hjorth, J., & Kouveliotou, C. 2002, GCN Circ, 1785
Wang L. and Wheeler J.C., 1998, ApJ, 504, L87
Wang, L., Howell, D. A., Höflich, P., Wheeler, J. C. 2001, ApJ, 550, 1030
Waxman, E. & Draine, B. T. 2000, ApJ, 537, 796
Waxman, E. 2004, ApJ, 602, 886
Weiler, K.W., Panagia, Nino, Montes, M.J., Sramek, R.A. 2002, ARA&A, 40, 387
Wheeler, J. C., Levreault, R. 1985, ApJ, 294, L17
Wheeler, J. C., Harkness, R.P. 1986, in “Galaxy distances and deviations from universal expansion”, Proceedings of the NATO Advanced Research Workshop, Kona, HI, Jan. 13-17, 1986. Dordrecht, D. Reidel Publishing Co., 1986, p. 455
Woosley, S. 1993, ApJ, 405, 273
Woosley, S. E., Eastman, R.G., Schmidt, B.P. 1999, ApJ, 516, 788
Yonetoku, D., Yamazaki, R., Nakamura, T., Murakami, T. 2005, MNRAS, submitted, astro-ph/0503254
Zeh, A., Klose, S., Hartmann, D. H. 2004, ApJ, 609, 952
Zwicky, F. 1938, ApJ, 88, 529