Supernovae Shed Light on Gamma-Ray Bursts

We have believed for decades that supernovae were the most magnificent and energetic phenomena occurring in the Universe after the Big Bang. Today we know that this is only a part of the story. Astronomers have discovered that comparable amounts of energy (or even more) are released, in a few seconds, by gamma-ray bursts. Recently it was determined that these two classes of events have a deep connection. In this article we report the observations of supernovae associated with gamma-ray bursts carried out at ESO by our group. We also briefly review the status of the supernova/gamma-ray burst connection and highlight the open questions.

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Entirely new areas of astronomical research sprouted out of the US political decisions arising from the Sputnik crisis. The race to space was primarily designed to reduce the "missile gap" evidenced by the crisis, but also to develop a space-based monitoring of the Soviet nuclear program, that had resumed extensive testing in the atmosphere. In addition, the need to counter the low-morale effects of the crisis and regain international prestige led to increased support for publicly exciting scientific investigations and explorations of space. The birth of extrasolar high-energy astrophysics (Giacconi et al. 1962) is certainly among the most important outcomes of this new political environment. Another exciting fruit of those times was the serendipitous discovery of gamma-ray bursts (GRBs). The first report about their cosmic origin came from the Vela satellites (Klebesadel, Strong & Olson 1973), launched to monitor compliance with the nuclear partial test ban treaty. We now know that GRBs are sudden and powerful flashes of gamma-ray radiation, which 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 10^{-3}s to about 10^{3}s and is clearly bimodal (Kouveliotou et al. 1993). The bimodality is also apparent from the spectral properties: long bursts ($T > 2$ s) tend to be softer than the short ones (Fig. 1). Klebesadel et al. (1973) pointed out the lack of evidence for a connection between GRBs with supernovae (SNe), as proposed by Colgate (1968), nevertheless they concluded that "*...the lack of correlation between gamma-ray bursts and reported supernovae does not conclusively argue against such an association...*". This was perhaps the very beginning of the galactic/extragalactic controversy on the origin of GRBs. Indeed

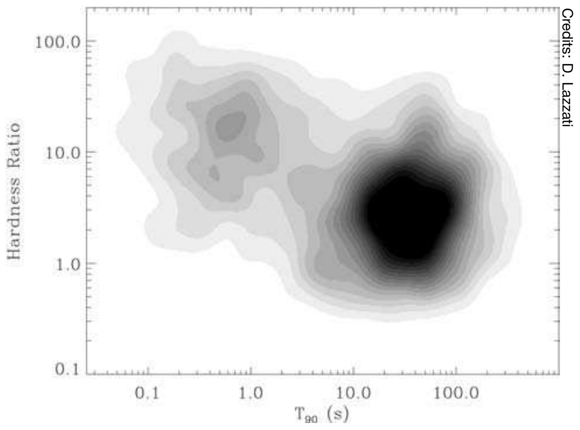

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Figure 1: Distribution of GRBs in the plane spectral hardness vs duration (T_{90} is the time within which 90% of the counts are collected). Two classes of events emerge, called respectively "long" and "short" GRBs.

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the distance scale of GRBs remained a mystery for 25 years. By the mid-1980s the general belief was that GRBs originate from neutron stars harbored in the Milky Way. But this idea received a surprising blow in the middle of the 1990s, after the observations of the Compton Gamma-ray Observatory: "*...the positions of over 1000 gamma-ray bursts detected with the BATSE experiment onboard the Compton Gamma-ray Observatory are uniformly and randomly distributed in the sky with no significant concentration to the Galactic plane or to the Galactic center*" (Paczynski 1995). However the observed isotropic distribution of GRBs was not considered the ultimate evidence in favor of an extragalactic origin (Lamb 1995). A public debate of these issues took place in April 1995 in the main auditorium of the Smithsonian Natural History Museum in Washington: Bodhan Paczynski argued that GRB go off at cosmological distances, whereas Donald Lamb contended that GRBs originate from neutron stars in an extended halo around the Galaxy.

The SN/GRB association

Thanks to observations with *BeppoSAX*, the Italian-Dutch satellite for X-ray astronomy (e.g. Boella et al. 1997), the X-ray and optical afterglows of GRBs could be discovered (Costa et al. 1997; van Paradijs et al. 1997), leading to a revolution in the study of these enigmatic astrophysical phenomena. The optical counterparts, in particular, yielded the redshift of GRBs, thus establishing that most of them originate at cosmological distances. It took only a handful GRBs to find the first at a redshift $z > 4$: indeed, with an average $z \cong 1$, GRBs are amongst the most remote cosmological objects we know of.

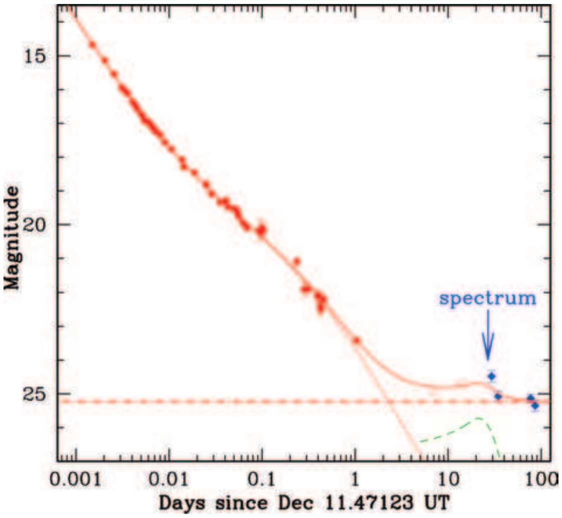

Figure 2: Light curve of the afterglow of GRB 021211; blue diamonds represent our data, while red circles are taken from the literature (see Della Valle et al. 2003 for a list of references). The dotted, dot-dashed and dashed lines represent the afterglow, host, and SN contribution respectively. The solid line is the sum of the three components.

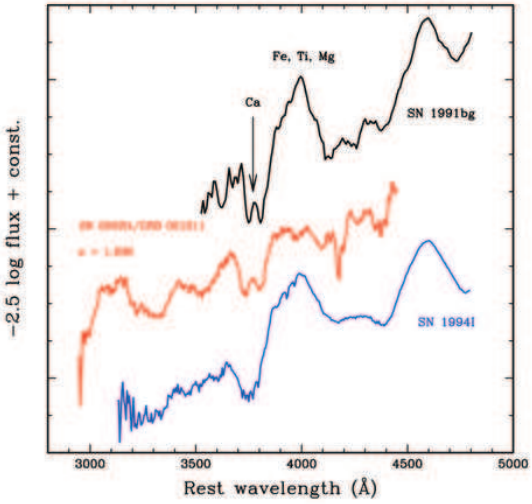

Figure 3: Spectrum of the bump of GRB 021211 (red line) compared with the spectra of the type-Ia SN 1991bg and of the type Ic SN 1994I. The broad deep is due to the blend of the Ca H+K edges, a common feature among SNe. From Della Valle et al. (2003).

The quarter-century dispute on the GRB distance and energetic scale was finally settled. GRBs were thus seen to involve the release of huge amounts of energy, comparable to the binding energy of a neutron star ($\leq 10^{53}$ ergs). Therefore, independent of any specific model, it appeared likely that GRBs (at least the long-duration ones, that is, those lasting more than 2 s), could be associated with the collapse of massive stars (Woosley 1993). Currently several lines of evidence support this scenario. **i**) 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 underenegetic 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 larger than those of normal Ib/c SNe and was characterized by an exceptionally high luminosity. This association was thus considered suggestive, rather than representative, of the existence of a general SN/GRB connection. **ii**) The light curves of many afterglows show rebrightenings which have been interpreted as emerging supernovae outshining the afterglow several days after the GRB event (e.g. Bloom et al. 1999). However, other explanations, such as dust echos, thermal re-emission of the afterglow, or thermal radiation from a preexisting SN remnant 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 ~100 Å.

SN 2002lt/GRB 021211

One of the first opportunities to carry out spectroscopic observations during a GRB afterglow rebrightening arrived in late 2002 (Della Valle et al. 2003). GRB 021211 was detected by the HETE–2 satellite, allowing the localization of its optical afterglow. We thus performed late-time follow-up photometric observations with the ESO VLT–UT4 (Yepun), during the period 2003 January–March. Figure 2 shows the results of our observations, together with those available in the literature. A rebrightening is apparent, starting ~15 days after the burst and reaching the maximum (R~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 our late-time images. We obtained a spectrum of the afterglow + host with FORS 2 (grism 150I) on Jan 8 (27 days after the GRB), during the rebrightening phase. The resolution was about 20 Å, and the integration time was 4 h. Fig. 3 shows our spectrum in the rest frame of the GRB (red solid line), smoothed with a median filter and cleaned from the nebular emission line [O II] 3727 Å (observed at 7473 Å, thus implying a redshift $z = 1.006$). 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 ~3770 Å (in the rest frame of the GRB), whereas its blue wing extends up to ~3650 Å. The comparison with the spectra of SN 1994I, and to some

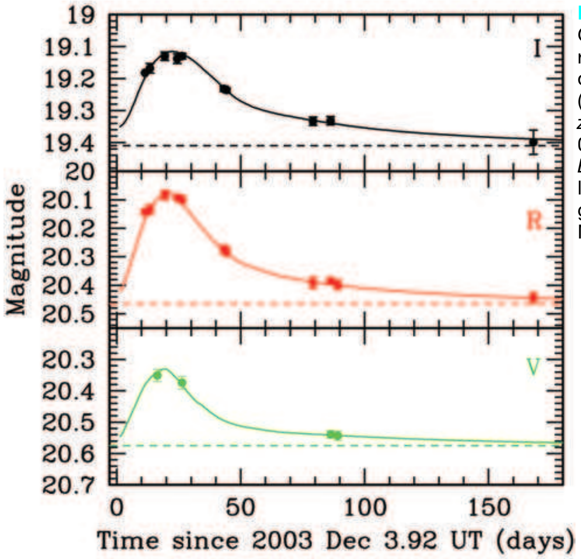

Figure 4: Light curves of GRB 031203. The solid line represents the contribution due to a 1998bw-like SN (Galama et al. 1998) at $z = 0.1055$, brightened by 0.5 mag and reddened with $E_{B-V} = 1.1$. The dashed lines represent the host galaxy contribution. From Malesani et al. (2004).

extent also of SN 1991bg and SN 1984L (the latter not plotted in Fig. 3) strongly supports the identification of the broad absorption with a blend of the Ca II H and K lines; the blueshifts corresponding to the minimum of the absorption and to the edge of the blue wing imply velocities $v \sim 14{,}400$ km/s and $v \sim 23{,}000$ km/s, respectively. The exact epoch when the SN exploded depends crucially on its rising time to maximum light. SN 1994I, SN 1998bw, and SN 1999ex (the best documented examples of type-Ic SNe) reached their B-band maximum ~12, 16, and 18 days after the explosion. In Fig. 2 we have added the light curve of SN 1994I (dereddened by $A_V = 2$ mag) to the afterglow and host contributions, after applying the appropriate K-correction (solid line). As 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 is also acceptable given the uncertainties in the measurements.

It is interesting to note that SN 1994I, the spectrum of which provides the best match with the observations, is a typical type-Ic event rather than an exceptional 1998bw-like object, as the one proposed for association with GRB 980425 and other well-studied examples (GRB 030329: Stanek et al. 2003; Hjorth et al. 2003; GRB 031203: Malesani et al. 2004). The peak magnitude of SN 1994I was $M_V \sim -18$, a not unusual value among type-Ic SNe, to be compared with the extraordinary brightness $M_V \sim -19.2$ reached by SN 1998bw or $M_V \sim -19.7$ achieved by SN 2003lw (associated with GRB 980425 and GRB 031203, respectively). If the SN associated with GRB 021211 indeed shared the properties of SN 1994I, this would open the interesting possibility that GRBs may be associated with normally-energetic type-Ic SNe, and not only with the more powerful events known as "hypernovae". We note however that the recently studied SN 2002ap (Mazzali et al. 2002) shared some of the properties of hypernovae (high expansion velocity, large kinetic energy), but was not significantly brighter than normal type-Ic SNe. Even if its pre-maximum spectra showed significantly broader lines than those measured in our case, this difference was vanishing at later stages, so that it may not be easy to distinguish between the two SN types.

We finally stress that even if GRBs are indeed mainly associated with normal type-Ic SNe, the discovery of overluminous type-Ic events (like SN 1998bw) associated with GRBs is favored by observations, since the SN can more easily dominate the afterglow component.

THE "SMOKING GUN": GRB 030329/SN 2003dh

The peculiarity of the SN 1998bw/GRB 980425 association (very faint gamma-ray emission, unusual afterglow properties, overluminous associated SN) and the objective difficulties to collect data for SN 2002lt at $z = 1$ (4 h to get one single spectrum) prevented us from generalizing on 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, discovered by the HETE-2 satellite, was found at a redshift $z = 0.1685$, relatively close-by, therefore allowing detailed photometric and spectroscopic studies. SN features were singled out in great detail by several groups, among which the GRACE collaboration (Hjorth et al. 2003). The associated SN (SN 2003dh) looked strikingly similar to SN 1998bw. However, the gamma-ray and afterglow properties of this GRB were not unusual among GRBs. Therefore, the link between GRBs and SNe was eventually established to be general, likely concerning all "classical", cosmological GRBs. In this respect GRB 980425 was considered a very peculiar event, unique among the ~40 GRBs with known redshift.

MORE CONNECTIONS: GRB 031203/SN 2003lw

GRB 031203 was a 30 s burst detected by the INTEGRAL burst alert system (Mereghetti et al. 2003) on 2003 Dec 3. Its precise (2.7′) localization was distributed within only 18 seconds from the beginning of the burst, the best combination between accuracy and speed ever reached for a GRB. At $z = 0.1055$, it was the second closest burst after GRB 980425. At this low redshift, the burst energy was extremely low, of the order of 10^{49} erg, well below the "standard" reservoir ~2 10^{51} erg of normal GRBs (Frail et al. 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).

We observed this event with the VLT and NTT telescopes on a number of epochs, to seek the signatures of a SN (Tagliaferri et al. 2003). Our observations are plotted in Fig. 4. A few days after the GRB, a rebrightening is apparent in all optical bands. The rebrightening amounts to ~30% of the total flux (which is dominated by the host galaxy), and is coincident with the center of the host galaxy to within 0.1″ (~200 pc). For comparison, we plot in Fig. 4 the VRI light curves of SN 1998bw (solid lines; from Galama et al. 1998), placed at $z = 0.1055$ and dereddened with $E_{B-V} \sim 1.1$. Interpolation of the $UBVRI$ data was performed in order to estimate the fluxes of SN 1998bw at the frequencies corresponding to the observed bands. Even after correcting for cosmological time dilation, the light curve of SN 2003lw is broader than that of SN 1998bw, and requires an additional stretching factor of ≈ 0.9 to match the R and I bands. The R-band maximum is reached in ~18 (comoving) days after the GRB. Assuming a light curve shape similar to SN 1998bw, which had a rise time of 16 days in the V band, our data suggest an explosion time nearly simultaneous with the GRB. However, given that SN 2003lw was not strictly identical to SN 1998bw, and as we lack optical data in the days immediately following the GRB, a lag of a few days cannot be ruled out. Type-Ic SNe usually reach V-band maximum in ~12–20 days, the brightest events showing a slower evolution.

A precise determination of the absolute magnitude of the SN is made difficult by the uncertain extinction. Based on the Balmer ratios of the host galaxy we derive the average combined Galactic and host extinction to be $E_{B-V} \sim 1.1$. Given the good spatial coincidence of the SN with the center of the host, such a value is a good estimate for the SN extinction. With the assumed reddening, SN 2003lw appears brighter than SN 1998bw by 0.5 mag in the *V, R,* and *I* bands. The absolute magnitudes of SN 2003lw are hence $M_V = -19.75 \pm 0.15$, $M_R = -19.90 \pm 0.08$, and $M_I = -19.80 \pm 0.12$.

Figure 5 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 2004 Mar. 1 (81 rest-frame days after the GRB). This assumes that the latter spectrum contains only a negligible contribution from the SN, which is confirmed by the photometry. The spectra of SN 2003lw are remarkably similar to those of SN 1998bw obtained at comparable epochs (shown as dotted lines in Fig. 8). Both SNe show very broad absorption features, indicating large expansion velocities, thus we classified SN 2003lw as a hypernova. The broad peaks near 5300 Å and 6600 Å are the emission components of P-Cyg profiles due to the blending of several lines. There is evolution between the two epochs: the bluer bump is observed at longer wavelengths in the second spectrum, and is slightly narrower. Moreover, the shape of the redder peak is different in the two epochs. Both peaks appear at redder wavelengths than in SN 1998bw. GRB 031203 was quite similar to GRB 980425, albeit more powerful. Both events consisted in a single, underenergetic pulse. Their afterglows were very faint or absent in the optical, and showed a very slow decline in the X-rays. Last, 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 10^5 to 10^6 times smaller than that probed by classical, distant GRBs with $\langle z \rangle \approx 1$, the rate of these events could be dramatically larger, perhaps they are the most common GRBs in the Universe.

The parent galaxy of GRB 031203 has been studied in detail by Chincarini et al. (2004) and Prochaska et al. (2004). These authors found that the GRB host is a star forming galaxy with a fairly high (relative to the local Universe) star formation, of the order of 10 M /yr/L*. This independently corroborates the existence of a link with the death of massive stars.

...There is an expanding frontier of ignorance...[2]

All these facts provide robust empirical grounds to the idea that some types of core-collapse SNe are the progenitors of long-duration GRBs. On the other hand, the existence of a SN/GRB association 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 indicate that the parent SN population of GRBs is formed by the bright tail of hypernovae, that is peculiar type-Ib/c SNe which are characterized by high/intermediate luminosity peaks ($M_B \sim -19.5$ to -17) and high expansion velocity of the ejecta (~30,000 km/s). However, there is growing evidence that standard Ib/c SNe or dim hypernovae (like SN 2002ap) can also be connected with GRBs and possibly with X-Ray flashes (Fynbo et al. 2004). Even type IIn SNe cannot be excluded (Garnavich et al. 2003). The possibility that GRBs/XRFs are connected with standard-type Ib/c SNe, and perhaps with some other class of core-collapse SNe, would have dramatic implications for the rate of occurrence of GRBs and their energy budget; **2.***Which is the relationship between the SN magnitudes at maximum light and the gamma-ray energy budget?* Taking at face values the associations SN 1998bw/GRB 980425, SN 2002lt/GRB 021211, SN 2003dh/GRB 030329, SN 2003lw/ GRB 031203, it looks like bright SNe might be associated to faint GRBs and viceversa; **3.** *Are the "red bumps" always representative of the signatures of incipient SNe?* Or can some of them be produced by different phenomena (e.g. echos)? To date, only for GRB 021211/SN 2002lt (Della Valle et al. 2003) has a spectroscopic confirmation been obtained. On the other hand, it is puzzling that Garnavich et al. (2003) and Fynbo et al. (2004) did not find clear SN features in the bumps of GRB 011121 and XRF 030723 respectively; **4.** *Is the lack of an optical bump indicative of the lack of a supernova?* Or rather do GRBs have a heterogeneous class of progenitors including SNe of different magnitudes at maximum and merging between compact objects; **5.** *What causes some small fraction of SNe Ib/c to produce observable GRBs, while the majority do not?*

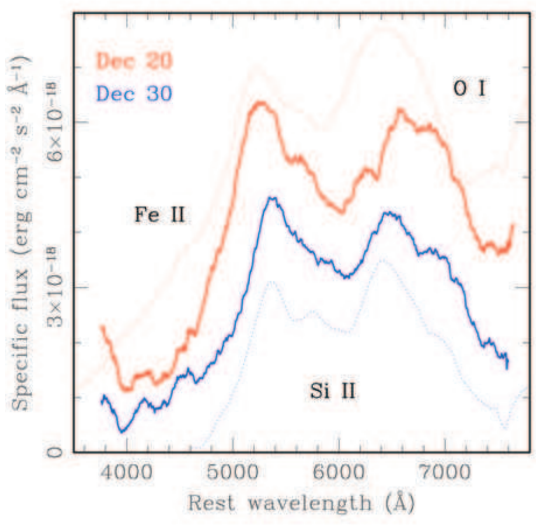

Figure 5: Spectra of SN 2003lw, 3 days before (Dec 20) and 7 days after (Dec 30) its *V*-band maximum light. Dotted lines show the spectra of SN 1998bw taken at similar epochs. From Malesani et al. (2004).

With an expected rate of discovery of about 1 event/week (observable from Paranal), the *Swift* satellite (Gehrels et al. 2004) will allow the GRB community to obtain in the next 2 to 3 years an accurate spectroscopic classification for dozens of SNe associated with GRBs and to provide conclusive answers to several of the above questions.

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[2] From R. Feynman, Six Easy Pieces, Chapter 1.