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Supernovae and Gamma-Ray Bursts

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Abstract I review the observational status of the Supernova/Gamma-Ray Burst (GRB) connection. Available data suggest that Supernovae (SNe) associated with GRBs form an heterogeneous class of objects including bright and faint hypernovae (Hyp) and perhaps also 'standard' Ib/c events. Current estimates of SN and GRB rates and beaming angles yield ratios GRB/SNe-Ibc $\sim 2\%$ and GRB/Hyp $\sim 25\%$. In the few SN/GRB associations so far discovered the SN and GRB events appear to go off simultaneously, although data do not exclude that the SN may precede the GRB by a few days.

Key words: stars – supernovae – Gamma-Ray Burst

1 INTRODUCTION

Optical, infrared and radio follow-up of GRBs, occurred in the last decade, have established that at least a significant fraction of long-duration GRBs (Klebesadel 1990; Dezalay et al. 1992; Kouveliotou et al. 1993) originate in supernova explosions. Direct evidence is provided by a handful of SN-GRB associations such as: SN 1998bw/GRB 980425 (Galama et al. 1998), SN 2003dh/GRB 030329 (Stanek et al. 2003, Hjorth et al. 2003), SN 2003lw/GRB 031203 (Malesani et al. 2004), SN 2002lt/GRB 021211 (Della Valle et al. 2003), XRF 020903 (Soderberg et al. 2005) and GRB 050525A (Della Valle et al. 2006). In addition there are about a dozen afterglows which show, days/weeks after the gamma-ray events, rebrightenings in their lightcurves (e.g. Zeh et al. 2004). These bumps are interpreted as SNe emerging out of their afterglows (Bloom et al. 1999).

2 CIRCUMSTANTIAL EVIDENCES

SN 1998bw was the first SN discovered spatially ($P \sim 10^{-4}$) and temporally coincident with a GRB (GRB 980425; Galama et al. 1998). SN 1998bw was discovered in the nearby galaxy ESO 184-G82 at $z = 0.0085$. This implied that GRB 980425 was underenegetic by about 4 orders of magnitudes with respect to the "standard" γ-energy budget of $\sim 10^{51}$ erg. The associated SN was extremely energetic with expansion velocities 3–4 times higher than those exhibited by normal Ib/c SNe. The peak of luminosity, $\sim 10^{43}$ erg s^{-1} (for a distance to SN 1998bw of ~ 40 Mpc) is about 10 times brighter than typical SNe Ib/Ic (Clocchiatti & Wheeler 1997), therefore suggesting that a large amount of $^{56}\mathrm{Ni}$ 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 originated in 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. This picture is consistent with the radio properties of SN 1998bw, which can be explained in terms of an interaction of a mildly relativistic ($\Gamma \sim 1.8$) shock with a dense circumstellar medium (Kulkarni et al. 1998, Weiler et al. 2002) due to a massive progenitor that has entirely lost its H envelope. Höflich, Wheeler & Wang (1999) presented an alternative scenario based on the hypothesis that all SNe-Ic are the results of aspherical explosions. According to different combinations of the geometry of the explosion and line of sight of the observer, the apparent luminosity of a SN may vary up to 2 mag, keeping the explosion energy ($\sim 2 \times 10^{51}$ erg) similar to that of 'normal' core-collapse supernovae. Maeda et al. (2002, 2005), after analyzing the Fe and [O I] line profiles

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in the nebular 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.

However, the association between two peculiar astrophysical objects such as SN 1998bw and GRB 980425 was not believed representative of the existence of a general SN/GRB connection.

Among circumstantial evidences, we should also include:

a) The late decline light curves of several afterglows show rebrightenings that have been interpreted in terms of emerging supernovae outshining the respective afterglow days/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) could not be ruled out on the basis of the photometric evolution, only spectroscopic observations during the rebrightening phase could remove the ambiguity.

b) The detection of star–formation features in the host galaxies of GRBs (Djorgovski et al. 1998, Fruchter et al. 1999) has independently supported the existence of a link with the death of massive stars. Le Floc'h et al. (2003) and 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$^{-1}/L^\star$ or more.

3 SN 2002LT/GRB 021211

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). Figure 1 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 ~ 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 (Fig. 1, right panel) 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 other SNe 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 $v \sim 14\,400$ km s^{-1} and $v \sim 23\,000$ km s^{-1}, respectively. The exact epoch when the SN exploded depends crucially on its rising time to maximum light. For example SN 1999ex, SN 1998bw and SN 1994I reached their V-band maximum ~ 18, 16 and 12 days after the explosion (Hamuy 2003). In Figure 1 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. 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* (hypernova is a 'peculiar' type SN-Ib/c, which ejecta are characterized by an high kinetic energy content, about an order of magnitude larger than observed in "standard" Ib/c events) 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).

4 GRB 030329/SN 2003DH AND GRB 031203/SN 2003LW

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. 2). 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.

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

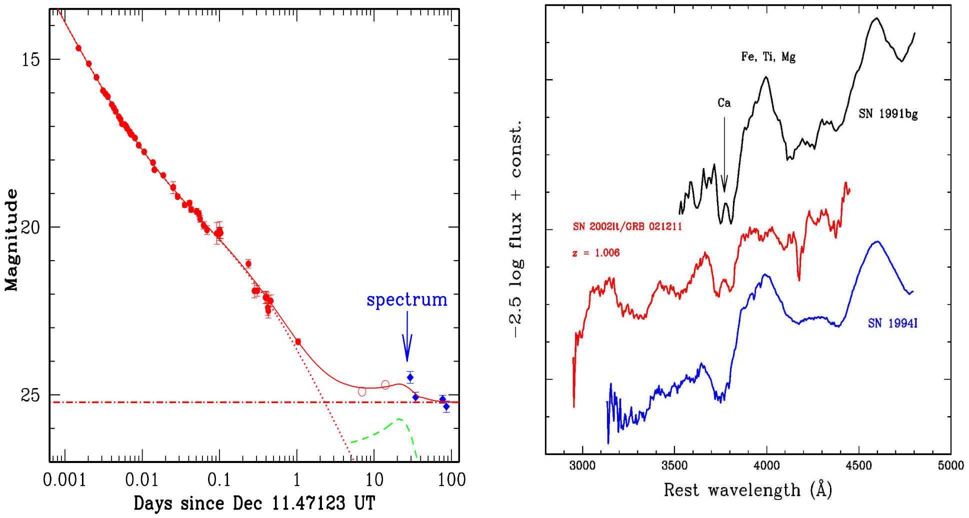

Fig. 1 **Left panel.** Light curve of the afterglow of GRB 021211. Filled circles represent data from published works (Fox et al. 2003; Li et al. 2003; Pandey et al. 2003), open circles are converted from HST measurements (Fruchter et al. 2002), while filled diamonds indicate our data; the arrow shows 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.

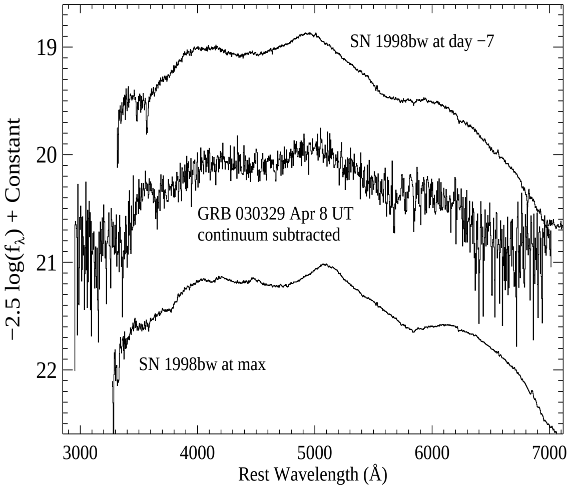

Fig. 2 Spectrum of 2003 April 8 with the smoothed spectrum of April 4 scaled and subtracted. The residual spectrum shows broad bumps at approximately 5000 and 4200 Å (rest frame), which is similar to the spectrum of the peculiar type-Ic SN 1998bw a week before maximum light (Patat et al. 2001). Plot from Stanek et al. 2003.

main sequence. 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.

GRB 031203 was a 30 s 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 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). 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 $0.1''$ (~ 200 pc). For comparison, in Figure 3 the VRI light curves of SN 1998bw are plotted (solid lines; from Galama et al. 1998), placed at $z = 0.1055$ and dereddened with $E_{B-V} = 1.1$. 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. 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 $M_I = -19.80 \pm 0.12$. Figure 3 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. 3). Both SNe show very broad absorption features, indicating high expansion velocities. The analysis of early spectra of 2003lw (Mazzali et al. 2006) indicates that this Hypernova produced a large

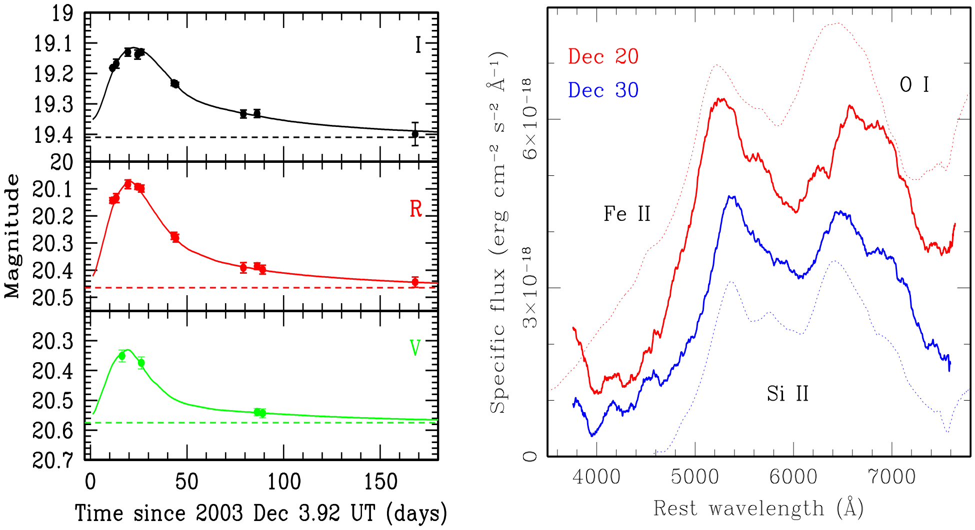

Fig. 3 **Left panel.** Optical and NIR light curves of GRB 031203 (circles). The solid curves show the evolution of SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999), rescaled at $z = 0.1055$, stretched by a factor 1.1, extinguished with $E(B-V) = 1.1$, and brightened by 0.5 mag. The dashed lines 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 250Å 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.

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.

5 RATES

All hypernovae reported in Table 1 have been not discovered during time ‘controlled’ surveys and this fact prevents us to derive the SN rate through the control-time methodology (Zwicky 1938). In this case a possible approach to derive the rate of hypernovae is to compute the frequency of occurence of all SNe-Ib/c and hypernovae in a limited distance sample of objects and to assume that they have been efficiently (or inefficiently) monitored by the same extent. 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^{-1}. This velocity threshold is suitable to make the distance distribution of ‘normal’ Ib/c and hypernovae statistically indistinguishable (KS probability=0.42). After excluding SN 1998bw, because it was searched in the error-box of GRB 980425, one can infer that the fraction of hypernovae is about $7/91 \simeq 8\%$ of the total number of SNe Ib/c. For a “Milky-Way–like” galaxy with $L_B = 2.3 \times 10^{10} L_{B_{\odot}}$ (Cox 2000) and a rate of 0.14 SNe-Ib/c per century and per 10^{10} $L_{B\odot}$ (Cappellaro, Evans & Turatto 1999), we obtain a rate of type Ib/c SNe of $\sim 3.2 \times 10^{-3}$ yr^{-1} and therefore a hypernova rate of $\sim 2 \times 10^{-4}$ 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 (Madau, Della Valle & Panagia 1998) and the B luminosity of the Milky Way. This approach gives $R_{\rm GRB} \sim 10^{-7}$ yr^{-1} that has to be rescaled for the jet beaming factor $f_{\rm b}^{-1}$. There exist different estimates for this parameter: from ~ 500 (Frail et al. 2001) to ~ 75 (Guetta, Piran & Waxman 2005). These figures imply that the ratio GRB/hypernovae spans the range: $\sim 25\% - 4\%$, while the ratio GRB/SNe-Ibc: $\sim 1.6\% - 0.2\%$. These data do not support the ratio GRB/Hypernova=1 proposed by Podsiadlowski et al. 2004, unless to assume $f_{\rm b}^{-1} \sim 2000$. We notice that $f_{\rm b}^{-1} \sim 2000$ is definitely larger than measured by Frail et al. 2001, Yonetoku et al. 2005, and Guetta et al. 2004, who found 500, 300 and 75, respectively.

Table 1 Hypernovae

SN	cz km s^{-1}	References
1997dq	958	Mazzali et al. 2004
1997ef	3539	Filippenko 1997
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
2005kz	8117	Filippenko, Foley & Matheson 2005

6 DISCUSSION

From the data presented in the previous sections a number of facts emerge:

1. Long duration GRBs are closely connected with the death of massive stars. This has been spectroscopically confirmed over a large range of redshifts: from $z = 0.008$ up to $z = 0.6$ (and possibly up to $z \sim 1$).
2. It is not clear whether or not only hypernovae are capable to produce GRBs or also “standard” Ib/c events (e.g. Della Valle et al. 2003, Fynbo et al. 2004). There is weak evidence (see Valenti et al. 2005) that other type of core-collapse can contribute to originate GRBs.The best evidence for the case of

an association between a Supernova IIn and a GRB has been provided by GRB 011121/SN 2001ke (Garnavich et al. 2003).

3. Available data (see Della Valle 2005 and references therein) indicate that the magnitude at maximum of SNe associated with GRBs spans a range of 5 magnitudes. However all GRB-SNe which have so far received the spectroscopic confirmation appear to belong to the bright tail of SNe-Ib/c population. If this is the effect of an observational bias (which favors the spectroscopic observations of bright SNe) operating on a small number of objects or it has a deeper physical meaning is not yet clear.
4. In Table 2 we have reported the estimates of the lags between the SN explosions and the associated GRBs, as measured by the authors of the papers. After taking these data at their face value, it is apparent that the SNe and the associated GRBs occur simultaneously, or the SN precedes the GRB by a few days at the most.

Table 2 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
		–	–2	Matheson et al. 2003a
GRB 031203	2003lw	0	–2	Malesani et al. 2004
GRB 041006	bump	2.7	–0.9	Stanek et al. 2005
GRB 050525A	bump	0	–6	Della Valle et al. 2006

5. Only a very small fraction of all massive stars are capable to produce GRBs. According to the current SN and GRB rates and $\langle fb^{-1}\rangle$ estimates, only $\sim 2\%$ of SNe-Ibc (or $\sim 25\%$ of Hypernovae) are able to produce GRBs. This implies that GRB progenitors must have some other special characteristic other than being just massive stars. Recent studies have extensively discussed the role that stellar rotation (Woosley & Heger 2006), binarity (Podsiadlowski et al. 2004, Mirabel 2004) and asymmetric explosions (Maeda et al. 2006) play in the GRB phenomenon.
6. The "optical" properties (i.e. luminosity at peak and expansion velocities) of the 3 closest SNe associated with GRBs vary by at most $\pm 30\%$, while the γ-budget covers about 4 order of magnitudes. These facts may be interpreted in at least 2 different ways: a) we may be seeing intrinsically similar phenomena under different angles. GRB 030329/SN 2003dh may be viewed almost pole-on, GRB 980425/SN 1998bw considerably off-axis ($\theta = 15^\circ - 30^\circ$, Maeda et al. 2005), while GRB 031203/SN 2003lw may lie in between (Ramirez-Ruiz et al. 2005). A consequence of this scenario is that the γ-properties are a strong function of the angle, whereas the optical properties are almost no affected by this relative small range of viewing angles ($\Delta\theta < 30^\circ$); b) there is an intrinsic dispersion in the properties of the relativistic ejecta for SNe with similar optical characteristics. This is not unconceivable after keeping in mind that the observed relativistic energies at play in the GRB phenomenon vary in the range $\sim 10^{47} - 10^{51}$ erg, which is only a fraction of the kinetic energy involved in the 'standard' SNe-Ibc (10^{51} erg) or hypernova (10^{52} erg) explosions.
7. As for AGN, it has been proposed (Lamb et al. 2005, see also Kouveliotou et al. 2004 and Dado et al. 2004) a unification scheme where GRBs, XRRs, XRFs and SNe-Ibc are the same phenomenon, but viewed at different angles. Given the rates of GRBs and type Ibc SNe discussed in the section 6, the unification scenario would work for $\langle fb^{-1}\rangle \sim 30000$, which would correspond to beaming angles of $\sim 0.5^\circ$. This picture is not supported by current studies (Guetta et al. 2005, Yonetoku et al. 2005; Frail et al. 2001) that suggest $\langle fb^{-1}\rangle$ to be in the range 100–500, corresponding to beaming angles of $\sim 8^\circ - 4^\circ$.

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