

The Supernova Gamma-Ray Burst Connection

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ABSTRACT: Observations show that at least some gamma-ray bursts (GRBs) happen simultaneously with core-collapse supernovae (SNe), thus linking by a common thread nature's two grandest explosions. We review here the growing evidence for and theoretical implications of this association, and conclude that most long-duration soft-spectrum GRBs are accompanied by massive stellar explosions (GRB-SNe). The kinetic energy and luminosity of well-studied GRB-SNe appear to be greater than those of ordinary SNe, but evidence exists, even in a limited sample, for considerable diversity. The existing sample also suggests that most of the energy in the explosion is contained in nonrelativistic ejecta (producing the supernova) rather than in the relativistic jets responsible for making the burst and its afterglow. Neither all SNe, nor even all SNe of Type Ibc produce GRBs. The degree of differential rotation in the collapsing iron core of massive stars when they die may be what makes the difference.

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1 INTRODUCTION

Gamma-ray bursts (GRBs), discovered by Klebesadel et al. (1973), are brief (\sim seconds), intense flashes of electromagnetic radiation with typical photon energies \sim 100 keV that arrive at Earth from unpredictable locations several times daily (e.g., Fishman and Meegan, 1995). They are isotropically distributed on the sky and, so far as we know, none has ever repeated¹. The production of GRBs is believed to require some small amount of matter accelerated to ultra-relativistic speeds (e.g., Mészáros, 2002) and beamed to a small fraction of the sky (Frail et al., 2001). In many of the longer lasting events the total energy in gamma-rays, corrected for this beaming, is $\sim 10^{51}$ erg.

Core-collapse supernovae (SNe), on the other hand, are the explosive deaths of massive stars that occur when their iron cores collapse to neutron stars or black holes (e.g., Woosley and Janka, 2005). They are, in general, not accompanied by highly relativistic mass ejection, but are visible from all angles and last from weeks to months. They may be either of Type Ib or Ic, if their hydrogen envelopes are lost, or Type II if they are not (Filippenko, 1997). The total *kinetic* energy here is also $\sim 10^{51}$ erg, roughly the same as the energy of the jet that makes a GRB.

SNe are the most *powerful* explosions in the modern universe, rivaling in pure wattage the rest of the observable universe combined, but most of the emission, $\sim 10^{53}$ erg s⁻¹, is in neutrinos which are, unless one happens to be very nearby, unobservable. GRBs are the *brightest* explosions in the universe, in terms of electromagnetic radiation per unit solid angle, sometimes as bright as if the rest mass of the sun, 2×10^{54} erg, had been turned to γ -rays in only ten seconds. The light per solid angle from SNe is about ten orders of magnitude fainter.

Despite the similarity in kinetic energy scale, it was thought for decades that these two phenomena had no relation to one another (though see Colgate, 1968; Paczyński, 1986). This was largely because, until the late 1990's, no one knew just how far away — and hence how luminous — the GRBs really were. Indeed, the consensus in the mid 1990's was that even if GRBs were ever found to be of cosmological origin, they were likely the result of a merger in a degenerate binary system, such as double neutron stars (Blinnikov et al., 1984; Paczyński, 1986; Eichler et al., 1989; Narayan et al., 1992) or a neutron star and black hole (Narayan et al., 1991; Paczynski, 1991) and would not be found in conjunction with supernovae.

Beginning in 1997 with the localization of long-wavelength counterparts (Costa et al., 1997; van Paradijs et al., 1997) and the confirmation of the cosmological distance scale (Metzger et al., 1997)², it became increasingly clear that those well-studied GRBs were associated with young stars in distant actively star-forming galaxies, and not with old stars in mature galaxies, as expected of the merger hypothesis. Within a few years, evidence mounted against the merger hypothesis and implicated GRBs, to the surprise of many, as due to the death of massive

¹Not included in our review here are the “soft-gamma repeaters” (Woods and Thompson, 2005), related phenomenologically to classic GRBs but believed to be associated with highly magnetic neutron stars in the local group of galaxies (though see Tanvir et al., 2005). There is no known direct temporal connection of SGRs to supernovae.

²By 1997, most of the community had already come to accept a cosmological distance scale for GRBs because of the isotropic distribution of locations found by the Burst and Transient Source Experiment (Fishman and Meegan, 1995; Paczyński, 1995).

stars (§ 2.1.2).

This association with star formation did not require a causal connection though. Perhaps the young stars resulted in SNe that produced neutron stars or black holes which in turn made the bursts some time later. Nor was it clear that any supernova accompanying a GRB would be especially bright³. The watershed event that brought the SN–GRB connection to the forefront was the discovery of a GRB on April 25, 1998 (GRB 980425) in conjunction with one of the most unusual SNe ever seen, SN 1998bw (Galama et al., 1998). The SN and the GRB were coincident both in time and place. Theory had anticipated that event (Woosley, 1993), but not its brilliance. Though the physical connection was initially doubted by some, and GRB 980425 was very sub-energetic compared with most GRBs, the in-depth study of the “SN-GRB connection” began in earnest on that day (§ 2.1.4).

Aspects of the SN-GRB connection have been reviewed previously (Wang and Wheeler, 1998; van Paradijs et al., 2000; van Paradijs, 2001; Woosley et al., 2001; Wheeler, 2001; Weiler et al., 2002; Mészáros, 2002; Bloom, 2005; Piran, 2005; Matheson, 2005; Della Valle, 2005; Höflich et al., 2005), but usually as cursory overviews of the connection, or parts of larger reviews of GRBs in general. Here we review specifically the observations, history, and theory relating to the SN-GRB connection. Since, until recently, the only accurately known counterparts were for GRBs of the so called long-soft variety⁴, our discussion centers on these events (though see § 2.2 and § 2.3).

What we know now is that at least one other supernova besides SN 1998bw, namely SN 2003dh (§2.1.6), has happened nearly simultaneously with a GRB. This time the GRB (030329) was of a more normal energy. A compelling spectroscopic case can also be made for supernova associations with GRB 031203 (SN 2003lw) and possibly GRB 021211 (SN 2002lt). There have also been “bumps” in the optical afterglows of many GRBs (§ 2.1.5) consistent in color, timing and brightness with what is expected from Type I supernovae of luminosity comparable to SN 1998bw. Indeed, given the difficulties in making the key observations, the data and models we shall review (§ 2.1, § 2.4, and § 2.5) are consistent with, though not conclusive proof of, the hypothesis that *all* long-soft GRBs are accompanied by SNe of Type Ic⁵. Still, there is evidence for considerable diversity in the brightness, rise times, and evolution of these events. The well-studied SNe that accompany GRBs (GRB-SNe) also show evidence for *broad lines*, indicative of high velocity ejecta. This leads us to suggest a sub-classification of Type Ic SNe, called “Type Ic-BL” (whether they are associated with GRBs or not). Type Ic-BL is a purely observational designation, and makes no reference to a specific progenitor model (e.g., “collapsars”) nor to the model-specific energetics or brightness of the explosions. In the latter respect, the GRB modeling community has come to view the label of “hypernova” for typing GRB-SNe as somewhat

³Here we distinguish “supernova,” the sub-relativistic explosion of a stellar mass object, from the “optical afterglow” produced when the relativistic material responsible for a GRB impacts the surrounding medium (Mészáros and Rees, 1997; Piran, 2005).

⁴Though the light curves and spectra of cosmic GRBs are very diverse, they can be broadly categorized on the basis of duration and power spectrum into two groups (Kouveliotou et al., 1993; Fishman and Meegan, 1995) — “short-hard” bursts with a median duration of 0.3 s, and “long-soft” bursts with a median duration of 20 s. The average peak energy of the shorter class is about 50% greater than the long class - 360 keV vs 220 keV (Hakkila et al., 2000).

⁵A Type Ic supernova has no hydrogen in its spectrum and also lacks strong lines of Si II or He I that would make it Type Ib or Ia. See Filippenko (1997) for review.

narrow and subjective.

While all GRBs of the long-soft variety may be accompanied by SNe, not all SNe, or even all SNe of Type Ic-BL, make GRBs. But why should some stars follow one path to death and others, another? As described in § 3.3, *rotation* is emerging as the distinguishing ingredient. Though it is a conjecture still to be proven, GRBs may only come from the most rapidly rotating and most massive stars, possibly favored in regions of low metallicity. Ordinary SNe, on the other hand, which comprise about 99% of massive star deaths, may come from stars where rotation plays a smaller role or no role at all. Indeed, the SN-GRB connection is forcing a re-evaluation of the role of rotation in the deaths of all sorts of massive stars.

The continued observation of both GRBs and the SNe that accompany them should yield additional diagnostics that will help the community gain deeper insight in to both phenomena. Some of these diagnostics, especially those that might shed light on the prime mover, or “central engine” that drives all these explosions are discussed in § 3.4, and we end with a discussion of future directions in the field in § 4.

2 OBSERVATIONS

2.1 OBSERVATIONAL EVIDENCE FOR A SN-GRB ASSOCIATION

2.1.1 Early Indications

Colgate (1968), in the only paper to *predict* the existence of GRBs before their discovery, associated them with the breakout of relativistic shocks from the surfaces of SNe. This motivated the discoverers (Klebesadel et al., 1973) to search for SN-GRB coincidences, but none was found. We know now that the transients from breakout itself are too faint to be GRBs at cosmological distances⁶. Even with thousands more GRBs and hundreds of SNe localized by 1997, no clear observational connection could be established (e.g., Hartmann and Woosley, 1988).

Bohdan Paczyński, for years (e.g., Paczyński 1986; though see also Usov and Chibisov 1975), suggested a cosmological origin for GRBs, and pointed out that the requisite energy (in γ -rays) would be comparable to the (kinetic) energy of a supernova. When the first redshifts of GRBs were determined (Metzger et al., 1997; Kulkarni et al., 1998), the implied energies were up to $\sim 10^3$ times larger than 10^{51} erg. In fact, the largest inferred γ -ray energy exceeded the rest mass energy of a neutron star (Kulkarni et al., 1999). Later, however, with geometric corrections for beaming (Rhoads, 1997; Halpern et al., 2000), the total energy release in γ -rays came down to around 10^{51} erg (Kumar and Piran, 2000; Frail et al., 2001; Freedman and Waxman, 2001; Bloom et al., 2003; Friedman and Bloom, 2005), with a small, but significant number of bursts at lower energies (e.g., Soderberg et al., 2004b). That the actual energy release in long-duration GRBs and SNe is comparable is consistent with an association, but does not require a common origin. Similar energetics are expected from a variety of viable cosmological progenitors. Yet, even before direct confirmation, several independent lines of evidence pointed tantalizingly to a direct SN-GRB connection. On

⁶Aspects of the Colgate model remain viable. A relativistic blast wave interacting with a circumstellar medium might be a reasonable model for some events (Woosley et al., 1999; Matzner and McKee, 1999; Tan et al., 2001), especially if the ejecta are beamed.

length scales spanning parsecs (“circumburst”), to galaxies, to cosmic distances, GRBs revealed their origin.

2.1.2 Location In and Around Distant Galaxies

The various scenarios for making GRBs (§ 3.2) have implications for their observed locations. Since neutron stars experience “kicks” at birth, the long delay before coalescence would lead to bursts farther from star-forming regions (Paczynski, 1998; Livio et al., 1998; Bloom et al., 1999b; Fryer et al., 1999a; Belczynski et al., 2000) than very massive stars. Therefore, subarcsecond localizations of afterglows with respect to distant galaxies provided, early on, an indirect means for testing hypotheses about the progenitors. GRB 970228, for example, was localized on the outskirts of a faint galaxy, (van Paradijs et al., 1997) essentially ruling out (Sahu et al., 1997) disruptive events around a central massive black hole (Carter, 1992). Unfortunately, the imaging capabilities of current instruments cannot resolve the immediate environment ($\lesssim 100$ pc) of GRBs that originate beyond ~ 100 Mpc. Hence the location of individual bursts (for instance, in an H II region) cannot be used as a definitive test of their nature. However, statistical studies reveal a strong correlation of the locations with the blue light of galaxies (Bloom et al., 2002a; Fruchter et al., 2006). It seems that long-soft GRBs happen preferentially in the regions where the most massive stars die.

No host galaxy stands out as exceptional, yet, in the aggregate, they are faint and blue (Mao and Mo, 1998; Le Floch et al., 2003), systematically smaller, dimmer, and more irregular than M_* galaxies at comparable redshifts (Mao and Mo, 1998; Hogg and Fruchter, 1999; Djorgovski et al., 2003; Conselice et al., 2005; Wainwright et al., 2005). Of the more than 60 GRB hosts known, only one (GRB 990705) appears to be associated with a normal spiral (Masetti et al., 2000), and that could be a coincidence (given the large solid angle of a big face-on spiral, the GRB has a greater probability of having occurred at higher redshift than its putative host). No long-duration GRB has ever been definitively associated with an early-type galaxy⁷.

There is convincing spectroscopic evidence that typical GRB host galaxies are forming stars actively, perhaps at a higher rate per unit mass than field galaxies (Djorgovski et al., 2001; Christensen et al., 2004). Sub-mm observations of some GRB hosts once appeared to indicate the presence of large amounts (\sim hundreds $M_\odot \text{ yr}^{-1}$) of obscured star-formation (Berger et al., 2003a), but recent mid-infrared observations of the same galaxies suggest significantly smaller star-formation rates (Le Floch et al., 2006). There are indications (e.g., Bloom et al., 2001), in particular from the line ratios of [Ne III] to [OII], that the H II regions are especially hot, indicating a propensity of GRB hosts to make more massive stars. More recently, a growing body of absorption-line spectroscopic evidence suggests that GRB hosts — or more precisely, the regions through which GRB afterglows are viewed — are low in metallicity (Vreeswijk et al., 2001; Savaglio et al., 2003; Prochaska et al., 2004a) though it remains to be seen whether metallicities are significantly different from field galaxies and damped Lyman α

⁷One group’s photometry of the host of GRB 970508 (Chary et al., 2002) indicated a significant old population, but this was not confirmed by other groups. Furthermore, morphological analysis showed that the galaxy surface brightness fit better an exponential than an $r^{-1/4}$ profile (Fruchter et al., 2000).

systems at comparable redshifts. As a class, the hosts of long-duration GRBs thus appear to favor progenitors that are closely connected with metal-poor massive stars (see § 3.3.3).

The locations of long-duration GRBs on the largest scale — in redshift space — confirm the expectations from smaller spatial scales. The GRB rate appears to track the global star-formation rate (Loredo and Wasserman, 1998; Bloom, 2003; Firmani et al., 2004; Price and Schmidt, 2004; Natarajan et al., 2005; Jakobsson et al., 2005). This too implicates a progenitor that makes a GRB without appreciable (\gtrsim Gyr) delay following a starburst (Totani, 1997; Wijers et al., 1998). While bursts from massive stars could, in principle, be observable to redshifts of ~ 30 (Mészáros and Rees, 2003), bursts from merger remnants with long delay times since starburst (such as, perhaps, short-hard GRBs) should not be observed beyond $z \approx 6$: there would simply not be enough time since the formation of the first stars.

2.1.3 Absorption Spectroscopy

Absorption line spectroscopy of GRB afterglows can also constrain the environments around GRB progenitors (Perna and Loeb, 1998), on both galactic and stellar scales. The columns of neutral hydrogen and metals seen in absorption in the highest redshift GRBs are generally significantly larger than those seen through quasar sight lines (e.g., Savaglio et al., 2003). This is not necessarily an effect local to the GRB, but possibly a consequence of the location of GRBs in the inner regions of their host.

Spectroscopy of the afterglow of GRB 021004 revealed significantly blueshifted ($\gtrsim 100 \text{ km s}^{-1}$) absorption features relative to the highest z system (Chornock and Filippenko, 2002; Møller et al., 2002; Vreeswijk et al., 2004). While some have claimed that the high velocities could be due to radiative acceleration of the circumburst material (e.g., Schaefer et al., 2003), a more natural explanation appears to be that the absorption is due to fast moving Wolf-Rayet winds from the progenitor. Indeed detailed modeling of Wolf-Rayet winds and interactions with the interstellar medium appear to accommodate significant column densities at a variety of blueshifts extending out to $\sim 2000 \text{ km/s}$ (van Marle, Langer, & Garcia Segura 2005; although see Mirabal *et al.* 2002). High-resolution spectra of more recent bursts also appear to show WR features (e.g., Prochaska et al. 2006). The presence of fine structure lines of, for example, Fe^+ , indicates a warm, dense medium that has only been observed in Galactic WR winds and never been seen in any extragalactic sightlines. Interestingly, because of the redshifting of UV lines that would be otherwise inaccessible to groundbased spectroscopy, high resolution spectra of GRBs are now offering unique detailed diagnostics of WR winds. Circumburst diagnostics are discussed further in § 3.4.4.

2.1.4 GRB 980425 and SN 1998bw

GRB 980425 triggered detectors on board both BeppoSAX and BATSE (Kippen, 1998). At high energies, it was seemingly unremarkable (Kippen, 1998; Galama et al., 1998) with a typical soft spectrum ($E_{\text{peak}} \approx 150 \text{ keV}$) and moderate duration ($\Delta T \approx 23 \text{ sec}$). Within the initial 8 arcmin radius error circle was an underluminous ($0.02 L_*$) late-type galaxy (ESO184-G82; $z = 0.0085$, Tinney et al. 1998), found 2.5 days after the GRB to host a young supernova, designated

as SN 1998bw (Galama et al., 1998; Lidman et al., 1998; Sadler et al., 1998; Galama et al., 1998). On temporal and spatial grounds, the physical association of the GRB with the young supernova was initially controversial (Galama et al., 1998; Pian et al., 1998), but after a careful reanalysis of the X-ray data (Pian et al., 2000) the association of the GRB with the supernova was confirmed: consistent with the location of the SN was a slowly variable X-ray source. This transient X-ray source provided an improved spatial and temporal connection between the GRB and the SN. It is now widely accepted that GRB 980425 was coincident SN 1998bw (Kouveliotou et al., 2004).

The evolution of SN 1998bw was unusual at all wavelengths. The discovery of prompt radio emission just a few days after the GRB (Kulkarni et al., 1998) (Figure 1) was novel. Almost irrespective of modeling assumptions, the rapid rise of radio emission from SN 1998bw showed that the time of the SN explosion was the same as the GRB to about one day. The brightness temperature several days after the GRB suggested that the radio photosphere moved relativistically with $\Gamma \gtrsim 3$. Still, the total energy in relativistic ejecta was small, $\lesssim 3 \times 10^{50}$ erg (Li and Chevalier, 1999), about two orders of magnitude less than in the SN explosion itself.

The early optical spectrum of the SN stymied astronomers. Lidman et al. (1998) wrote: *“The relative intensity of the different regions of the spectrum is changing from day to day. The absence of H lines suggests that the object is not a Type-II supernova; the lack of Si at 615 nm indicates that it is not a regular Type-Ia supernova. The nature of this puzzling object still evades identification...”*. The initial IAUC-designated Type was that of a Ib (Sadler et al., 1998) but a reclassification to a “peculiar Type Ic” was suggested (Patat and Piemonte, 1998; Filippenko, 1998) when no He nor Si II $\lambda 6355$ was found. SN 1998bw peaked in the V-band 16.2 days (rest frame) after the GRB with $M_V = -19.16 \pm 0.05 + 5 \log h_{71}$ mag (Galama et al., 1998). Given the unknown peculiar velocity of the host and the uncertainty in the extinction along the line of sight, this absolute peak brightness is uncertain at the 10% level.

If GRB 980425 arose from the $z = 0.0085$ galaxy, then it must have been a very underluminous burst. Assuming isotropic emission, the energy in gamma-rays was $E_\gamma = 8.5 \pm 0.1 \times 10^{47}$ erg, more than 3 orders of magnitude fainter than the majority of long-duration GRBs (Frail et al., 2001; Bloom et al., 2003). Any collimation would imply an even smaller energy release in gamma-rays. Still, many held that on purely phenomenological grounds that GRB 980425 and SN 1998bw had to be physically associated. The SN was simply too unusual not be connected with the GRB.

Accepting the connection and given the very low redshift, the burst site of at least one (albeit faint) GRB was studied in unprecedented detail. The SN position was found with the *Hubble Space Telescope* (HST) to have been in an apparent star forming region within 100 pc of several young stars (Fynbo et al., 2000), as expected of core-collapse SNe. Likewise, late-time Chandra X-ray imaging revealed an X-ray point source (Figure 2) consistent with the optical and radio SN position (Kouveliotou et al., 2004) (and, curiously, a variable ultra luminous X-ray source in the same spiral arm). Even at such low redshifts, the late-time HST imaging was incapable of resolving any star cluster or companion. This fact serves as a bleak reminder that GRBs which occur at even higher redshifts may not have their progenitors nor immediate progenitor environments directly observed.

The unusual properties of the event led some to suggest that GRB 980425 represented not only a phenomenological sub-class of GRBs, but one physically distinct from other long-duration GRBs (Bloom et al., 1998; Norris et al., 1999; Woosley et al., 1999; Matzner and McKee, 1999; Tan et al., 2001). The consensus is now that both GRB 980425 and SN 1998bw, in particular the energetics of such, represent the extreme in a continuum of events all with same underlying physical model. Indeed GRB 031203 and its associated SN (§2.1.6) are now considered the closest cosmological instance of GRB 980425 and SN 1998bw (Soderberg et al., 2004b).

2.1.5 Late-time Bumps

Viewing GRB 980425, and its origin, as distinct from the “cosmological” set of GRBs was the norm in 1998. Though the detection of a contemporaneous SNe would be a natural consequence of a massive star origin (e.g., Woosley, 1993; Hansen, 1999), no other GRB had obvious late-time emission that resembled a supernova. A report of a red emission “bump” following GRB 980326 (Bloom and Kulkarni, 1998) was interpreted as due to a coincident SN at about a redshift of unity (Bloom et al., 1999a; Castro-Tirado and Gorosabel, 1999) (Figure 3). Without a spectroscopic redshift for GRB 980326 and multi-band photometry around the peak of the bump, the absolute peak brightness and type of the purported SN could not be known. The available data were also consistent with a dust echo (Esin and Blandford, 2000; Reichart, 2001) or dust re-radiation (Waxman and Draine, 2000) from material surrounding the GRB. A subsequent reanalysis of the afterglow of GRB 970228 revealed evidence for a bump which appeared to be the same absolute magnitude as SN 1998bw with similar rise times (Reichart, 1999; Galama et al., 2000; Reichart et al., 2000). Similar reports of bumps were made (Sahu et al., 2000; Fruchter et al., 2000; Björnsson et al., 2001; Lazzati et al., 2001; Castro-Tirado et al., 2001; Sokolov, 2001; Berger et al., 2001; Covino et al., 2003; Gorosabel et al., 2005a; Masetti et al., 2005), but none as significant and with as clear cut connection to SNe as GRB 980326 and GRB 970228 (see Bloom 2005).

Concerted multi-epoch ground-based and space-based observing campaigns following several GRBs strengthened the notion that late-time bumps were indeed SNe (Price et al., 2003; Bloom et al., 2002b; Garnavich et al., 2003b; Stanek et al., 2005). The SN of GRB 01121 showed a spectral rollover during peak at around 4000 Å, nominally expected of core-collapse SNe in the photospheric phase. The typing of the SN associated with GRB 011211 was controversial, with Garnavich et al. (2003b) showing evidence that the brightness and color evolution resembled 1998S (a Type II_n; see also Meurs and Rebeles 2004) and Bloom et al. (2002b) showing consistency with a Ic-like curve interpolated between the faint and fast 1994I and the bright and slow 1998bw. We discuss the overall census of GRB-SNe photometry in § 2.5.

2.1.6 Spectroscopic Evidence and a Clear Case

Though several bumps were found with characteristics remarkably similar to Type I SNe, the first truly solid evidence for a connection between ordinary GRBs and SNe came with the detection of the low-redshift ($z = 0.1685$; Greiner et al. 2003c) GRB 030329 and its associated supernova, SN 2003dh (for recent reviews,

see Matheson 2004 and Della Valle 2005). Shortly after its discovery (the brightest burst HETE-2 ever saw), the afterglow of the GRB (Peterson and Price, 2003; Torii, 2003) was very bright ($R \sim 13$ mag). It faded slowly, undergoing several major re-brightening events in the first few days (Burenin et al., 2003; Greiner et al., 2003a; Matheson et al., 2003c; Bloom et al., 2004; Lipkin et al., 2004). Given the low redshift, several spectroscopic campaigns were initiated. Spectra of the afterglow (Matheson et al., 2003a; Garnavich et al., 2003a; Matheson et al., 2003b; Chornock et al., 2003; Stanek et al., 2003; Kawabata et al., 2003; Hjorth et al., 2003), 6.6 and 7.7 days after the GRB, showed a deviation from a pure power-law and the emergence of broad SN spectral features (Figure 4).

As the afterglow faded, the SN became more prominent and showed remarkable similarity to SN 1998bw (Figure 5). Spectrapolarimetric observations at later times showed that the SN light was somewhat polarized ($P < 1\%$) indicating mild asymmetry in the sub-relativistic ejecta. Given the broad spectral features, indicating high velocities ($\gtrsim 25000$ km s $^{-1}$; Stanek et al. 2003; Hjorth et al. 2003; Mazzali et al. 2003), and apparent absence of hydrogen, helium and strong Si II $\lambda 6355$ absorption, a classification as Type Ic-BL was natural (Matheson et al., 2003c). We leave the discussion of the modeling of SN 2003dh to §3, but we emphasize here that even what should be the easiest-to-measure “observable” of a SN-GRB can be highly model dependent: the reported peak magnitude of SN 2003dh differed by more than 1 magnitude (from 0.6 mag fainter to 0.5 mag brighter than SN 1998bw) (Matheson et al., 2003c; Lipkin et al., 2004; Hjorth et al., 2003; Mazzali et al., 2003; Bloom et al., 2004). In part, the differences can be due to the quality of the observations near peak, but much of the difference can be ascribed to different assumptions regarding the extinction towards SN 1998bw, the modeled brightness of the afterglow at the time of peak, and the modeled k -corrections of the SN (1998bw) template.

There have been a few other reports of spectroscopic identifications of a SN associated with a cosmological GRB. A supernova-like brightening was first reported by Bailyn et al. (2003) at the position of the low redshift ($z = 0.1055$; Prochaska et al. 2004a) GRB 031203. The presence of SN 2003lw was confirmed photometrically in multiple optical and infrared bands (Bersier et al., 2004; Cobb et al., 2004; Malesani et al., 2004a; Gal-Yam et al., 2004). Spectra 17 and 27 days after the GRB exhibited broad spectral features reminiscent of SN 1998bw at similar epochs (Malesani et al., 2004a), but the light curve behavior was more of a broad plateau around peak than 1998bw (Cobb et al., 2004; Gal-Yam et al., 2004; Thomsen et al., 2004). Della Valle et al. (2003) reported both a bump and a low resolution spectrum at the position of GRB 021211 ($z = 1.006$). A recent claim of a SNe associated with Swift burst GRB 050525a has been made based upon a photometric bump and a low signal-to-noise spectrum near peak (Della Valle et al., 2006).

2.2 SHORT-HARD GAMMA-RAY BURSTS

“Short-hard bursts” constitute $\sim 30\%$ of the BATSE sample (Kouveliotou et al., 1993) and, if, as now appears likely, they typically are sampled from a smaller redshift than long soft bursts, they could be the most frequent form of GRB in the universe. Some models (Zhang et al., 2003; Waxman and Mészáros, 2003) predict an association of short hard bursts with massive star death, and hence with SNe.

Recently, however, the counterparts of several short hard bursts have been discovered (Gehrels et al., 2005; Bloom et al., 2005; Villasenor, 2005; Fox et al., 2005; Hjorth et al., 2005b; Soderberg et al., 2006a). These GRBs have been found at lower redshifts than typical long bursts, but it is not yet conclusively established that the true bursting rate is significantly skewed towards lower redshift (Gal-Yam et al., 2005; Prochaska et al., 2005; Fox et al., 2005; Bloom and Prochaska, 2006). Short bursts tend to have prompt burst energy releases much smaller than that of long bursts, and this may limit their detectability beyond redshifts of unity. Short bursts have not been found in regions of obvious active star formation (though two are on the outskirts of a starburst galaxy) (Prochaska et al., 2005; Soderberg et al., 2006a; Bloom and Prochaska, 2006). In fact, the hosts of 3 of the 5 well-localized short GRBs are elliptical galaxies (see also Berger et al. 2005 and Bloom et al. 2005). This strongly implicates old stars or stellar remnants as the progenitors of short-hard GRBs. This claim is buttressed by the fact that in at least two cases (GRB 050509b: Bloom et al. 2005 and Hjorth et al. 2005a; GRB 050709: Fox et al. 2005) the limits on any accompanying supernova are very tight, stronger than any limits placed on long-duration GRB counterparts. No supernova is present that is more than 1% as bright as SN 1998bw ($M_R > -12$ at 16 days in GRB 050709; Hjorth et al. 2005a). Still, the internal-external shock model for short-duration GRBs appears to accommodate the data (Lee et al., 2005; Bloom et al., 2005; Fox et al., 2005; Panaitescu, 2005).

With such a small sample, it would be prudent to wait (e.g., Bloom and Prochaska, 2006) before claiming that all short hard bursts are the result of merging compact objects, but the data so far are certainly consistent with that hypothesis. This raises the interesting possibility that we may need to define yet another class of “peculiar supernova” (mini-supernova?), if the radioactive ejecta of the mergers prove capable of powering a brief optical and X-ray display (Li and Paczyński, 1998; Kulkarni, 2006).

If short hard bursts are merging compact objects, the duration of the bursts also has some interesting implications for GRBs in general. Associating the event duration with the operation of the central engine implies that the viscous lifetime of any accretion disk created in the merger, typically $0.1 M_\odot$ (Rosswog et al., 2003; Setiawan et al., 2004) is ~ 0.1 s. This timescale is far too short for disk accretion to be the power source of long soft GRBs unless there is an additional mechanism for mass accretion onto the disk over longer timescales (§ 3).

2.3 COSMIC X-RAY FLASHES

Cosmic X-ray flashes (XRFs; Heise et al., 2001) are observationally similar to classic GRBs, only softer, with a similar distribution of durations (Sakamoto et al., 2004). An intermediary in the spectral continuum between XRFs and classic GRBs are the so-called X-ray rich GRBs (XRR). Although the cosmological distance scale was well established (Bloom et al., 2003), it was not until Soderberg et al. (2004a) determined a spectroscopic redshift ($z = 0.251$; XRF 020903) that the energetics of any XRF was firmly determined. While the brightness of XRFs implies a similar energy release (per solid angle) to GRBs, the internal-external shock model for the prompt and afterglow emission of XRFs is not as well established. No broadband study of the light curve of an XRF afterglow has been carried out, so the synchrotron origin, while consistent with the data, is uncertain.

Because of their similar characteristics to long-soft GRBs, it is generally thought that the underlying cause is the same (§ 3), i.e., the explosive death of a massive star. The emission could be softer because one is just outside the edge of an ordinary GRB jet (Yamazaki et al., 2003; Granot et al., 2005); because an ordinary GRB jet had a cocoon of relativistic matter directed towards us with a moderate Lorentz factor (Zhang et al., 2004); or because the jet itself had a larger baryonic loading and hence lower Lorentz factor (Zhang et al., 2004). The latter two explanations implicitly assume that the XRF is produced by an external shock where lower Lorentz factor correlates with softer spectra. The opposite behavior is expected in the internal shock model.

An important clue to the origin of XRFs came with the discovery of a supernova-like bump associated with XRF 020903 (Soderberg et al., 2004a). There was a clear rise and decay and, when a low S/N spectrum was obtained near peak, the galaxy-subtracted spectrum was a reasonably good match to the spectrum of SN 1998bw at a similar epoch. This suggests that at least one XRF originates from the death of a massive star.

However, aside from XRF 020903, a concerted search for SN signatures in XRFs 011030, 020427, 030723, 040701, 040812, and 040916 (Soderberg et al., 2005; Levan et al., 2005) turned up no clear evidence for associated SNe. A bump peaking in the R -band ~ 16 days after the XRF 030723 has been interpreted as a supernova at redshift ~ 0.5 (Fynbo et al., 2004; Tominaga et al., 2004). However, the optical spectrum showed no clear evidence for features and, more importantly, both the K -band (Soderberg, private communication) and X -ray light curve (Butler et al., 2005) appeared to track the R -band light curve. This is contrary to the expectation from a supernova, where the IR-optical colors evolve and the IR light luminosity peaks after the optical light. In other XRFs, no bump was seen. Most constraining is that any supernova in XRF 040701 ($z = 0.21$) would have to have been over 3 mag fainter than SN 1998bw (Soderberg et al., 2005), fainter than all GRB-SNe known to date⁸. Though fewer bump searches have been conducted for XRFs than for GRBs, the non-detections are significant because of the low average redshift of XRFs. The absolute magnitudes probed by deep (mostly HST) imaging rival all the bump searches in GRBs. Whereas all GRBs less than redshift 0.7 have *claimed* bump detections, six XRFs (one with redshift and two more with inferred redshifts less than unity) show no evidence for a SN-like bump. The search for SNe from XRR GRBs has been more successful, with at least two (041006 and 040924) showing strong evidence for late-time bumps (Soderberg et al., 2006b). Both appear at peak to have been fainter than SN 1998bw.

It may be that the SNe in XRFs are inherently faint (or absent), which would have important implications for the models, but the numbers are still small. Was XRF 020903 truly an XRF or an outlier in the classic GRB population? Could the optical extinction for XRF 040701 have been greater than estimated? Could the XRFs with no supernova bump and no well determined redshift be farther away than we think? The study of XRF related SNe will be a subject of great interest in the coming years.

⁸Note that no optical afterglow of any sort was seen in XRF 040701 so the optical extinction could not be measured as with GRB 011121 (Price et al., 2002). Therefore this quoted limit for an XRF-SN relies upon a rather uncertain estimate of the optical extinction based on the X-ray spectrum.

2.4 CHARACTERISTICS OF SUPERNOVAE ASSOCIATED WITH GRBS

The distinguishing feature of a GRB-SN that sets it apart from all other SNe is the concentration of significant kinetic energy in *relativistic* ejecta ($\beta\Gamma \gtrsim 2$). This does not necessarily require that the supernova be bright, or even exceptionally energetic, though GRB-SNe often are. It also does not preclude the existence of SNe without GRBs, powered by the same energy source (§ 3.4.2). But to produce a GRB, one needs at least as much energy in relativistic ejecta as is observed in γ -rays and afterglow emission. That is, $E_{\text{Rel}} \gtrsim E_{\gamma}$. The value of E_{γ} is difficult to measure directly because of the effects of beaming, but in typical bursts, it is around 10^{51} erg (Frail et al., 2001; Bloom et al., 2003). E_{Rel} can be inferred from radio observations at such late times that beaming is no longer important, and is $\sim 5 \times 10^{51}$ erg (Berger et al., 2003c, 2004). Of course, there can be considerable variation of both these numbers.

The SNe accompanying GRBs also differ from common SNe (Filippenko, 1997) in other ways (Table 1), most obviously the absence of hydrogen in their spectra: GRB-SNe appear to be Type I SNe. Indeed, where spectra of sufficient quality exist to be sure, the supernova is of Type Ic-BL. Some of the broad peaks seen in the GRB-SNe spectra are likely due to low opacity, rather than due to emission from a single ion spread over large velocity ranges (e.g., Iwamoto et al., 2003). Near maximum light GRB-SNe do appear to show broad absorption lines of O I, Ca II and Fe II (Iwamoto et al., 1998). About 7 days before maximum, the width of a weak Si II line in SN 1998bw suggested expansion speeds in excess of 30,000 km s⁻¹ (Patat et al., 2001). There has never been a photospheric spectrum of a confirmed GRB-SN that indicated the presence of H and no optical He I lines have been seen (e.g., $\lambda 6678$, $\lambda 7065$, and $\lambda 7281$), leading to a classification as a Type Ic⁹. The late time nebular phases (at least in the case of SN 1998bw) show lines of [O I], Ca II, Mg I, and Na I D (Sollerman et al., 2002).

As detailed in §2.5, the *median* peak magnitude of the *observed* GRB-SNe sample is comparable to that of Type Ia SNe. This large apparent brightness could be misleading however, because of the stringent requirements – rapidly declining optical afterglow, low red shift, faint host galaxy – required for detection (§ 2.5). In one case, GRB 010921, the upper limit on any supernova is absolute magnitude -17.7 and, as noted previously, some of the SNe with XRFs may be fainter still. Indeed, when the non-detections of GRB-SNe are accounted for, the inferred “true” mean of the sample ($M_V = -18.2 \pm 0.4 + 5 \log h_{71}$) is considerably fainter than the mean of normal Type Ia SNe.

At late times, the decay of ⁵⁶Co often leads to a steady exponential decline in the light curve of Type Ib SNe, providing all decay energy remains trapped. SN 1998bw initially declined somewhat faster than this, presumably because of γ -ray escape (McKenzie and Schaefer, 1999; Sollerman et al., 2002). At very late times ($\gtrsim 500$ days), a flattening seen in the light curve could be interpreted as greater retention of the energy from radioactive decay as well as the contribution of species other than ⁵⁶Co (Sollerman et al., 2002), but this could have other explanations. Other GRB-SNe could not be followed with sufficient sensitivity to see the exponential tail.

⁹An infrared feature observed in SN 1998bw may have been due to He (Patat et al., 2001) but that not a secure identification and, more important, the classification distinction between Ib and Ic depends on the observed presence or absence, respectively, of He I in the optical waveband (T. Matheson, private communication).

The radio emission of GRB 980425 and SN 1998bw showed no evidence for polarization (Kulkarni et al., 1998) which suggests that the mildly relativistic ejecta were not highly asymmetric, at least in projection. Still, internal Faraday dispersion in the ejecta would serve to suppress a radio polarization (Soderberg, private communication). The optical light of SN 1998bw showed significant evidence for polarization at the 0.5% level (Patat et al., 2001), which is consistent with polarization inferred in other core-collapse SNe (Wang et al., 1996; Leonard et al., 2002). This implies some degree of asphericity in the non-relativistic ejecta (e.g., Höflich et al., 1999), but, as Patat et al. (2001) noted, there is a degeneracy between the viewing angle and the level of asymmetry. Significant polarization was observed for the afterglow of GRB 030329 over many epochs, but by the time SN 2003dh dominated the optical light, two epochs of observations revealed only marginally significant polarization (Greiner et al., 2003a) (even then, the afterglow could have contaminated the polarization signal). While polarization is surely a critical ingredient towards understanding the SN explosion geometry, Klose et al. (2004) have pointed out that interstellar dust for mildly extinguished lines-of-sight should artificially induce polarization at the 1% level. Thus, even if polarization is detected in GRB-SNe, the interpretation is anything but straightforward.

In the case where the brightness is as great as Type Ia, theory demands a large production of ^{56}Ni (§ 3.4.1). In order to make so much ^{56}Ni , large shock energies and stellar masses are required, at least in one-dimensional models. The high energy is consistent with the rapid expansion velocities inferred from the spectra. The combination – high mass, large velocity, and big ^{56}Ni mass – implies kinetic energies $E_{\text{SN}} \sim 10^{52}$ erg. Since the collapse of the iron core to a neutron star, plus any accretion into a black hole must release $E_{\nu} \sim 10^{53}$ erg, one has the interesting energy relation, $E_{\nu} \gg E_{\text{SN}} \gtrsim E_{\text{Rel}} \gtrsim E_{\gamma}$. There may be significant gravitational radiation as well, with $E_{\text{GW}} \sim E_{\nu}$ (van Putten et al., 2004b). The energy in γ -rays is only a small fraction, $\sim 1\%$ of the total energy released in the explosion.

Table 2 gives the energetics and theoretical masses of ^{56}Ni produced in each of the three GRBs with definite spectroscopic SNe. For those GRBs which exhibit jet breaks and are thought to be observed nearly pole on, an actual E_{γ} can be inferred. In other cases, E_{Rel} probably provides an upper limit to E_{γ} , but E_{γ} could be much greater than $E_{\gamma,\text{iso}}$ if the event was observed off-axis. SN 2003lw had a light curve and spectrum similar to SN 1998bw and its energy and ^{56}Ni production are assumed here to be the same (Gal-Yam et al., 2004). It is noteworthy that E_{Rel} and E_{γ} for all three bursts in Table 2 are much less than the canonical 5×10^{51} and 10^{51} erg, respectively, mentioned above for common GRBs. This reflects, at least in part, the greater likelihood of discovering a supernova if the optical afterglow is faint.

So far, no clear correlation has been found between GRB properties, or even E_{Rel} , and the brightness or energy of the supernova, though the simplest theory would suggest that more energy input by the central engine would make both more ^{56}Ni and more relativistic ejecta.

The demographics of local Ibc SNe compared with the GRB rate can be used to constrain the frequency with which SNe accompany GRBs (whether the GRB is detected or otherwise). At optical wavebands, Type Ic-BL SNe like 1998bw comprise about $\sim 5\%$ of all Type Ibc SNe, which is to simply assert the unusual nature of 1998bw-like SNe. Radio surveys of local Ibc SNe at early times, reveal

that no more than 3% (Berger et al., 2003b) harbor SNe with relativistic ejecta like SN 1998bw. At late times, the radio emission from GRBs initially directed off axis should become observable as Γ of the shock slows to unity. Yet none of the local Ibc SNe studied show evidence for an off-axis jet with large relativistic energy. Specifically, at the 90% confidence level less than 10% of all Ibc harbor an ordinary off-axis GRB (Soderberg et al., 2006c). Moreover, the class of optical BL SNe cannot all be related to GRBs at the 84% confidence level (Soderberg et al., 2006c).

2.5 DO ALL GRBs HAVE SUPERNOVA COUNTERPARTS?

While 2003 was a banner year for the SN-GRB connection, there has since been a noticeable lack of new GRBs with spectroscopic SNe. Indeed, *most* long-duration GRBs do *not* have a detected associated supernova. Yet the indirect evidence (§ 2.1.2) supports the consensus view that most long-duration GRBs arise from the death of massive stars. These two statements can be reconciled by invoking observational biases which are either extrinsic or intrinsic to the explosions.

Extrinsic biases, those that result in the decreased probability for discovery even if the supernova is bright, are straightforward to enumerate:

1. *Localization* - Poor localizations of bursts from their afterglows dramatically hamper the ability for large aperture telescopes to discover emerging SNe. These poor localizations can be endemic to the detection scheme (e.g., BATSE) or because bursts are found in regions of the sky that are unfavorable for optical or X-ray followup (e.g., near the Sun). Afterglows are less likely to be found near full moon because of the brighter sky and less sensitive IR detectors. Likewise, if the bump peaks near full moon then the point source sensitivity is reduced.
2. *Dust* - Fainter SNe are expected from bursts that occur near the line-of-sight through the Galaxy, or in especially extinction-riddled regions of their hosts. GRB 021211 and GRB 031203 were behind significant Galactic columns, which diminished the sensitivity of the supernova observations.
3. *Redshift and luminosity distance* - With increasing luminosity distance comes higher distance modulus, but the k -corrections at optical wavelengths are particularly unkind beyond redshifts of $z \approx 0.5$. Absorption line blanketing due to metals (e.g., Fe) suppress the emissivity below the blackbody luminosity bluewards of $\sim 4000\text{\AA}$ making Type Ibc SNe especially difficult to detect at increasing redshift (Bloom et al., 1999a). We expect essentially no optical flux from GRB SNe at $z \gtrsim 1.2$. Since most Swift bursts have been found above redshift of unity, it is disappointing, but not surprising, that only one SN (associated with GRB 050525a) was found in the first 14 months of Swift observations.
4. *Host galaxies* - The host galaxies of GRBs, while generally fainter than L_* , can still contaminate the light of GRB SNe at late times. If all hosts were $0.1 L_*$, then the integrated light of hosts would be $M_V(\text{host}) \approx -19$ mag, comparable to the brightest SNe. Thus, without high resolution imaging to resolve out diffuse host light, or high signal-to-noise image differencing, finding the supernova point source is all but impossible for SNe that peak at magnitudes fainter than the integrated light of the hosts. Figure 6 makes this point rather dramatically. An important demonstration is that the SN

associated with GRB 031203 was only 0.22 magnitudes brighter than the host galaxy at peak. Had this burst originated from higher redshift, the photometric sensitivity would be diminished, and the SN might not have been discovered.

The biases against detection introduced by intrinsic properties of the explosions are less tractable. Local observations of Type Ibc SNe show a more than 5 magnitude spread in peak brightness, likely related to the diversity of dust extinction, the spread in explosion energy, and ^{56}Ni production. Rise times also range from \sim week to several weeks. SNe that make the same mass of ^{56}Ni but which peak later are fainter. An intrinsically faint supernova obviously has less of a chance of being detected. The GRB afterglow brightnesses at late times may also be comparable to or brighter than the peak of a supernova. It is again sobering to note that the supernova associated with GRB 030329 might never have been recognized at higher redshift. SN 2003dh was discovered spectroscopically when the SN contributed less than 5% of the total flux (Matheson et al., 2003c). If there is no obvious bump in the light curve when the supernova peaks (e.g., Lipkin et al., 2004), a photometry-only campaign could miss the SN altogether. Still, the supernova might be recovered with precision color photometry.

Zeh et al. (2004) published an important photometric study of bumps in GRBs, fitting 21 of the best sampled afterglows and finding evidence for 9 bumps. Statistically significant evidence for bumps are found in 4 GRB afterglows (990712, 991208, 011121, and 020405) while 5 have marginal significance (970228, 980703, 000911, 010921, and 021211). All of these GRBs had bumps claimed prior to the Zeh analysis. Zeh et al. (2004) emphasize that all GRBs with $z \lesssim 0.7$ appear to have bumps, which of course, would be expected if all long-duration GRBs have associated SNe. However, bump detection does not necessarily imply a SN detection. There are, in fact, important cases where multi-band photometry has shown that late-time bumps may not be due to a supernova. The late-time light curves of GRB 990712 and XRF 030723, for example (see § 2.3), do not appear consistent with a supernova. Figure 7 shows the results of our compilation of bumps and upper-limits from the literature.

If GRB-SNe are a particular subset of Type Ibc SNe, then it is useful to ask if the GRB-SNe sample draws only from the bright end of the Type Ibc distribution (Bloom, 2005; Soderberg et al., 2006b). Richardson et al. (2006) report the detailed modeling of 24 local Type Ibc supernovae and derive the distribution of peak absolute M_V accounting for Galactic and host extinction¹⁰. Figure 7, comparing the observed GRB-SNe population with the Richardson sample, makes clear that the *observed* GRB-SNe are at the bright end of the *observed* Type Ibc population. Here we use the GRB-SNe compilation from Table 1; in the case where a range of M_V was reported in the literature, we assume that M_V is the average of the two measurements that define that range (following from 1998bw, we also assume that $M_U - M_V = 0.19$ mag for GRB 021211). The *median* of the *observed* GRB-SNe sample is $M_V = -19.1 + 5 \log h_{71}$ mag whereas the *median* peak magnitude in the local Ibc sample is $M_V = -17.9 + 5 \log h_{71}$ mag.

A more subtle but important question is whether the *true* GRB-SNe distribu-

¹⁰In what follows, the Richardson et al. magnitudes have been re-calibrated to $H_0 = 71$ km s⁻¹ Mpc⁻¹. We have not included the peak M_V from SN 1999cq because that value is degenerate with 1994I (T. Matheson, private communication). The sample compiled by Soderberg et al. (2006b) contains a subset (13) Ibc SNe.

tion in peak magnitude, when non-detections are folded in, are consistent within having been drawn from the local Type Ibc population. Treating lower limits and insignificant bump measurements from the literature as non-detections of GRB-SNe, we find that the *mean* of the true underlying peak magnitude distribution (from the Kaplan-Meier estimator) is $M_V = -18.2 \pm 0.4 + 5 \log h_{71}$ whereas the *mean* peak magnitude in the local Ibc sample is $M_V = -18.3 \pm 0.2 + 5 \log h_{71}$ mag. By all relevant “survival analysis” tests (Lavalley et al., 1992), we conclude that the GRB-SNe population is statistically consistent with having been drawn from the same population as the local Ibc from Richardson et al.¹¹. Moreover, although the GRB-SNe population is consistent with both the Ib and Ic sample, the connection with Ic SNe is more heavily favored¹².

3 MODELS

3.1 CORE-COLLAPSE SUPERNOVA MODELS

Models for ordinary core-collapse supernovae have been extensively reviewed by Woosley and Weaver (1986); Bethe (1990); Burrows (2000); Woosley et al. (2002); Buras et al. (2003, 2006); Woosley and Janka (2005); Janka et al. (2005); Mezzacappa (2005). The current “standard model”, by no means universally accepted (Wheeler et al., 2005), begins with the collapse of the iron core of a highly evolved star that had a main sequence mass of over $10 M_\odot$. The collapse, triggered by electron capture and the partial photodisintegration of the iron at temperatures $T \sim 10^{10}$ K and densities $\rho \sim 10^{10}$ g cm⁻³, continues until the center of the central core exceeds nuclear density by a factor of about two. The rebound, generated by this overshoot and the short range repulsive component of the nuclear force, launches a shock wave, but this “prompt” shock wave quickly loses all outward velocity to due to photodisintegration and neutrino losses. By ~ 0.1 sec after the onset of the collapse, one has a “proto-neutron star” with radius ~ 30 km and mass $1.4 M_\odot$ with a standing accretion shock at ~ 150 km through which matter is falling at about $0.1 - 0.3 M_\odot \text{ s}^{-1}$.

Over the next tenth of a second or so, the neutron star radiates a small fraction of its binding energy as neutrinos, $L_\nu \sim 10^{53}$ erg s⁻¹. Approximately 10% of these capture on nucleons in the region between the neutron star and accretion shock. This energy deposition drives vigorous convection which helps transport energy to the shock and also keeps the absorbing region cool enough that it does not efficiently re-radiate the neutrino energy it absorbed. If $\sim 10^{51}$ erg can be deposited in a few tenths of a second, the accretion can be shut off. The continuing neutrino energy deposition then inflates a bubble of radiation and pairs that pushes off the rest of the star making the supernova. If not, accretion continues until a black hole is formed. In this standard model, rotation and magnetic fields are assumed to have negligible effect.

The problem with this scenario, as many have noted, is that it not robust in

¹¹That is the probability that the observed deviation is due to random chance is greater than 0.3 for all tests (e.g., the Generalized Wilcoxon Tests). We have assumed no censoring of the local Ibc data; since bright Ibc systematically detected over faint Ibc, this clearly biases the Ibc sample to brighter magnitudes.

¹²Specifically, $P(\text{Gehan's Generalized Wilcoxon Test}) = 0.14$ comparing the GRB-SNe sample to local Ib SNe and $P(\text{Gehan's Generalized Wilcoxon Test}) = 0.96$ when comparing to local Ic SNe. Other tests show similar improvements for the Ic comparison.

the computer simulations. More often than not, the neutrino energy deposition, by itself, fails to launch and sustain an outbound shock of greater than about 10^{51} erg, as is required by analysis of SN 1987A (e.g. Bethe, 1990), observations of the light curves of ordinary Type IIp supernovae (Woosley and Weaver, 1986; Elmhamdi et al., 2003; Chieffi et al., 2003), supernova remnants and ISM heating (Dickel et al., 1993; Thornton et al., 1998), nucleosynthesis constraints (Woosley and Weaver, 1995), and neutron star masses (Timmes et al., 1996). If the explosion energy is too weak, large amounts of matter fall back producing a black hole and robbing the Galaxy of the necessary iron and other heavy elements. As of this writing it remains unclear whether the problem with the models is "simply" one of computational difficulty¹³ or whether key physics is lacking. If additional physics is required, rotation and magnetic fields are the leading candidates. However, it remains possible that the answer is being affected by uncertainties in the high density equation of state, changes in fundamental particle physics (especially neutrino flavor mixing), or the possible role of vibrational energy (Burrows et al., 2006).

3.2 THE GRB CENTRAL ENGINE

The general theory of GRBs, with some discussion of models has been recently reviewed by Mészáros (2002) and Piran (2005). Unlike a model for supernovae alone, a viable GRB model must deliver, far away from the progenitor star, focused jets with at least 200 times as much energy in motion and fields as in rest mass. The jet typically must have an opening angle ~ 0.1 radian and a power $\sim 10^{50}$ erg s⁻¹. In addition, at least occasionally, the model must deliver $\sim 10^{52}$ erg of kinetic energy to a much larger solid angle (~ 1 radian) to produce supernovae like SN 2003dh and SN 1998bw. This is ten times more than an ordinary supernova.

Except in the *supranova* model (§ 3.2.3), the fact that a relativistic jet must escape the host star without losing too much of its energy severely constrains the model for the central engine. Zhang et al. (2004) have shown that the jet head travels significantly slower than the speed of light and requires 8 – 25 s to reach the surface for jet energies from 3×10^{48} erg s⁻¹ to 3×10^{50} erg s⁻¹ (Figure 8). If the jet is interrupted or changes its orientation significantly in that time, the flow rapidly degrades to subrelativistic energies and is incapable of making a GRB. Thus acceptable models must provide $\gtrsim 10^{50}$ erg s⁻¹ of relativistic, beamed energy for $\gtrsim 10$ s. If, for example, one accepts that the duration of short hard bursts (~ 0.3 s) reflects the activity of a central engine, the energy source for short hard bursts and long soft ones cannot be the same. Similarly, any model that delivers its energy impulsively, on a time scale much less than 10 seconds, will not make a GRB, even if that energy is initially large and highly focused.

3.2.1 The Millisecond Magnetar Model

Building on earlier models of electromagnetic explosions (Usov, 1992; Thompson, 1994; Meszaros and Rees, 1997), many groups (Wheeler et al., 2000; Drenkhahn and Spruit, 2002; Lyutikov and Blackman, 2001; Lyutikov and Blandford, 2003)

¹³The correct calculation must be done in three dimensions to capture the complex fluid flow in the convective region where the neutrinos deposit their energy, and the neutrino transport itself must be followed in great detail and coupled to the hydrodynamics

have developed models in which the energy source for GRBs is the rotation of a highly magnetized neutron star with an initial period of about one ms (i.e., rotating near breakup). For a rotational velocity $\Omega \sim 5000 \text{ rad s}^{-1}$ and a dynamo-generated magnetic field, $B \sim 2 \times 10^{15} \text{ G}$, the rotational energy, $E \sim I\Omega^2/2 \sim 10^{52} \text{ erg}^{14}$ and the dipole spin down luminosity, $L \sim B^2 R^6 \Omega^4 / c^3 \sim 10^{50} \text{ erg s}^{-1}$, are typical of GRBs and the supernovae that accompany them. Thompson et al. (2004) have considered the coupling between the neutrino-powered wind that must accompany any proto-neutron star going through its Kelvin-Helmholtz contraction (Duncan et al., 1986; Qian and Woosley, 1996) and the strong magnetic field of a ms magnetar. Large powers, up to $10^{52} \text{ erg s}^{-1}$ can, in principle, be extracted by a centrifugally driven wind. The strength of these models is that they relate GRBs to the birth of an object known to exist, the magnetar, with an energy scale that is about right for a neutron star rotating near break up. The Poynting flux models further offer the possibility of highly energetic outflows with essentially no limit on the Lorentz factor (Blandford, 2002). The fields required $\gtrsim 10^{15} \text{ G}$ are large, but no larger than in other models.

So far, however, all these models ignore the accretion, $\gtrsim 0.1 M_{\odot} \text{ s}^{-1}$, that occurs onto the proto-neutron star for several seconds before it contracts to its final radius and develops its full rotation rate. This accretion must be reversed before the neutron star becomes a black hole. The models are also characterized by a monotonically declining power. Though they do not, so far, consider the two events separately, an initial blast to a large solid angle is probably necessary to explode the star and make the necessary ^{56}Ni (§ 3.4.1). A declining power would be available 10 s later to make the GRB itself. It may be that the neutron star models require the initial operation of a successful neutrino-powered explosion before they can function (Fryer and Warren, 2004).

3.2.2 Collapsars

The necessary conditions to make a collapsar are black hole formation in the middle of a massive star and sufficient angular momentum to make a disk around that hole (Woosley, 1993; MacFadyen and Woosley, 1999). The angular momentum needed is at least the value of the last stable orbit around a black hole of several solar masses, $j = 2\sqrt{3}GM/c = 4.6 \times 10^{16} M_{\text{BH}}/3 \text{ cm}^2 \text{ s}^{-1}$ for a non-rotating hole (where M_{BH} is the black hole mass in solar units) and $j = 2/\sqrt{3}GM/c = 1.5 \times 10^{16} M_{\text{BH}}/3 \text{ cm}^2 \text{ s}^{-1}$ for a Kerr hole with $a=1$. This compares with an angular momentum in the ms magnetar model of $j = R^2\Omega \sim 5 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ if $\Omega \sim 5000 \text{ rad s}^{-1}$ and $R = 10 \text{ km}$. Since the black holes in the collapsar model are typically very rapidly rotating and since the specific angular momentum at $3 M_{\odot}$ is always greater than that at $1.5 M_{\odot}$, the minimum angular momentum requirements of the collapsar and ms magnetar model are similar. Interestingly, there may also be a *maximum* value of j for the collapsar to work (MacFadyen and Woosley, 1999; Narayan et al., 2001; Lee and Ramirez-Ruiz, 2005). If j is too great, the disk forms at too great a radius to effectively dissipate its binding energy as neutrino emission and photodisintegration. The collapsar model additionally invokes the formation of a black hole which seems likely above some critical mass (§ 3.3.1).

Provided a disk and hole form (Figure 9), the greatest uncertainty in this model

¹⁴The moment of inertia of a neutron star for an appropriate range of masses and radii is $0.35 MR^2$ (Lattimer and Prakash, 2001)

is the mechanism for turning disk binding energy or black hole rotation energy into directed relativistic outflows. Three possible mechanisms are discussed: 1) neutrinos (Woosley, 1993; Popham et al., 1999; Narayan et al., 2001; Di Matteo et al., 2002); 2) magnetic instabilities in the disk (Blandford and Payne, 1982; Proga et al., 2003); and 3) MHD extraction of the rotational energy of the black hole (Blandford and Znajek, 1977; Lee et al., 2000; Mizuno et al., 2004). In the first case, neutrino pairs are generated in the hot disk and impact one another with the greatest angle along the rotational axis. Efficient energy deposition is favored by large angle collisions and the small volume of the region, especially for Kerr black holes, but probably the efficiency is no greater than $\sim 1\%$ of the total neutrino emission, or $\sim 10^{51}$ erg. As the estimate of the total energy in the relativistic component of a GRB has come down in recent years, the neutrino version of the collapsar model has become more attractive. However, up to three orders of magnitude greater energy is available from methods that more directly tap the gravitational potential of the disk or the rotation of the black hole. The neutrino version produces a hot, high entropy jet, while some versions of the MHD models produce colder, Poynting flux jets (§ 3.2.4).

In the collapsar model, the supernova and the GRB derive their energies from different sources. The supernova, and the ^{56}Ni to make it bright, are produced by a disk “wind” (MacFadyen and Woosley, 1999; MacFadyen, 2003; Kohri et al., 2005). This wind is subrelativistic with a speed comparable to the escape velocity of the inner disk, or about $0.1 c$ (Figure 10). If $1 M_{\odot}$ accretes to make the GRB and half of this is lost to the wind, this is 10^{52} erg. The wind begins as neutrons and protons in nearly equal proportions and thus ends up, after cooling, as ^{56}Ni . This nickel probably comes out in a large cone (polar angle ~ 1 radian) surrounding the GRB jet though it might get mixed to other angles during the explosion.

In numerical simulations so far, the explicit MHD processes that drive the wind have not been followed. An α -viscosity is used instead and the wind is driven by thermal dissipation. Thus the larger energy (10^{52} erg) of the supernova definitely has an MHD origin (if only the disk instabilities responsible for its viscosity, Balbus and Papaloizou (1999)) while that of the GRB remains ambiguous. There are also versions of the collapsar model in which the black hole is not made promptly by the failure of the initial shock to truncate accretion, but by fall back in a supernova that explodes with insufficient energy for all its matter to escape (MacFadyen et al., 2001) and in pair instability supernovae at high red shift (Fryer et al., 2001). Both of these variations probably give transients that last longer than the typical value, 20 s, for “long” soft GRBs, but if they are to work, the energy source must be MHD. Neutrino annihilation is too inefficient for the low accretion rate in the fall back model and large black hole radius in the pair-instability model.

It is a prediction of the collapsar, (though possibly the other models as well), that the central engine remains active for a long time after the principal burst is over, potentially contributing to the GRB afterglow (Burrows et al., 2005). This is because the jet and disk wind are inefficient at ejecting all the matter in the equatorial plane of the pre-collapse star and some continues to fall back and accrete (MacFadyen et al., 2001).

Finally, the collapsar model attempts to explain the time structure of GRBs and to produce the variable Lorentz factor necessary for the internal shock model to function (Piran, 2005). The jet, as it passes through the star, is modulated by

its interaction with the surrounding matter (Zhang et al., 2003). That is, even a jet introduced with constant power in the star’s center emerges with a highly variable density and energy at the surface. However, this interaction happens far from the central engine and would be present in any model where a relativistic jet of radiation and matter must penetrate the star.

3.2.3 Supranovae

The maximum mass for a differentially rotating neutron star can be up to $\sim 50\%$ larger than in the non-rotating case (T. Gold as cited in Bladford and Rees, 1972; Morrison et al., 2004). This gives baryonic maximum masses around 3 – 3.5 solar masses, well above the largest iron core masses expected in massive stars (Woosley et al., 2002). Uniform rotation causes less of an increase, $\sim 20\%$. The simplest version of the supranova model (Vietri and Stella, 1998) assumes that such a “hypermassive” neutron star initially forms with a mass above the critical value for a slowly rotating neutron star. The external star is blown away in an initial supernova that makes the neutron star. Some time later, years in the original model, dipole radiation slows the neutron star to the point that it collapses to a black hole. For a soft equation of state with an adiabatic index $\Gamma - 4/3 \ll 1$, as much as 10 – 20% of the mass of the collapsing neutron star avoids capture and goes into a disk about the central hole (Shapiro, 2004; Duez et al., 2004). This disk accretes and a GRB jet is produced by MHD processes. The supernova evacuates the near region of troublesome baryons that might contaminate the jet and also provides a shell of heavy elements about 10^{16} cm from the burst. The discovery of x-ray lines in the afterglows of some GRBs provided support for this model (Vietri et al., 2001), but to the extent that the lines themselves have become questionable (§ 3.4.5), that motivation is less compelling. The disk, neutron-star combination produced here is similar to that in models for short hard bursts (§ 2.2) and to the extent that those are inherently less energetic than long soft bursts, one wonders if there is sufficient energy and duration for a long soft burst.

It is clear in the case of events like GRB 980425 and GRB 030329 that the supernova and the GRB happened nearly simultaneously — within a few days of each other at most. Delays between several hours and several months are also ruled out because neither the GRB jet nor its emissions would escape the still compact supernova. Nevertheless the model is not ruled out for those GRBs in which no supernova has been observed, nor is it ruled out for situations in which the delay is seconds rather than years. Since the critical mass for differential rotation is considerably larger than for rigid rotation, there is a range of masses for which simply enforcing rigid rotation (while conserving angular momentum) will lead to collapse. Baumgarte et al. (2000) estimate the magnetic braking time to be

$$\tau_B \sim \frac{R}{v_a} \sim 1 \left(\frac{B}{10^{14} \text{ G}} \right)^{-1} \left(\frac{R}{15 \text{ km}} \right)^{-1/2} \left(\frac{M}{3 M_\odot} \right)^{1/2} \text{ s}. \quad (1)$$

It is unclear whether the outcome of an object experiencing such a collapse is deformation, accompanied by gravitational radiation, complete collapse, or collapse to a black hole plus a disk. In any case, this might be a transition object along the way to the collapsar model. Indeed, for the angular momentum that is invoked, a hypermassive neutron star rotating at break up is a likely, though often ignored initial stage in the collapsar model.

3.2.4 Poynting flux or fireball?

Related to the uncertainty in the birth of the GRB jet in the above models, is a key uncertainty in the nature of the jet itself. Does it consist of hot baryons, thermally loaded with radiation and pairs greatly exceeding the rest mass (Piran, 1999; Mészáros, 2002), or is the “jet” characterized by large scale magnetic fields, dynamically dominant and present from start (at the central engine) to finish (in the afterglow) (Meszaros and Rees, 1997; Lyutikov and Blackman, 2001; Blandford, 2002; Lyutikov et al., 2003)? In the latter case the baryons play little role and may as well be absent.

Numerical simulations (Aloy et al., 2000; Zhang et al., 2004) show that relativistic fireballs, given mild initial collimation, can pass through stars of solar radius and exit the star with their large energy per baryon intact. No such calculations exist yet for Poynting flux jets to show that their ordered electromagnetic energy does not become thermalized on the way out. This difficulty might be overcome once the jet has bored a hole so that there is a low density (albeit optically thick) line of sight to the center of the star. That is, a jet could initially be a fireball and make a transition early in the burst to being Poynting flux dominated.

The most important characteristic, observationally, of Poynting flux models is that there are no internal or reverse shocks. In the model developed by Lyutikov and Blandford, the GRB emission comes from 10^{16} cm not 10^{13} cm. Poynting flux models have the capability of producing large polarization (Lyutikov et al., 2003) which might be a diagnostic of the model. A strong early optical afterglow, as in GRB 990123, may also be easier to accommodate in Poynting flux models (Zhang and Mészáros, 2002; Fan et al., 2004). Poynting flux models also predict no high energy neutrino flux accompanying the GRB, but do predict that GRBs could be the site of ultra-high energy cosmic rays (Blandford, 2002).

3.3 PROGENITOR STARS

All GRB progenitors must lose their hydrogen envelope prior to death. The radius of even a blue supergiant is several hundred light seconds and the head of the jet which is to make the GRB travels significantly slower than light while inside the star (Zhang et al., 2003, 2004). One might envision situations where a very asymmetric supernova might occur, powered by the same central engine as a GRB, but a 20 s gamma-ray burst of the common variety is very unlikely. This is consistent with the observation that the limited set of spectroscopic SNe associated with GRBs are, so far, of Type I. The progenitors must also be massive enough and occur frequently enough to explain the observed statistics. Finally, since only a small fraction of massive stars make GRBs when they die, special circumstances must be involved.

3.3.1 Mass

Single stars over about $10 M_{\odot}$ on the main sequence are required in order to make an iron core and collapse to a compact remnant. Stars of still higher mass produce more massive iron cores and have greater accretion rates onto that core once it collapses. Higher mass stars also have greater gravitational binding energy outside the iron core (Woosley et al., 2002). Both effects make an explosion more difficult. It has been speculated that above some critical mass, a black hole

forms before an outgoing shock is launched (Fryer, 1999), setting the stage for the collapsar model. For a somewhat smaller mass, a black hole could still form from fallback (MacFadyen et al., 2001), though the accretion goes on at a much lower rate. For stars that do not make black holes, the faster rotation associated with neutron stars resulting from the death of the most massive stars (Heger et al., 2005) still makes them more promising GRB progenitors. The necessary helium core mass to make a GRB is probably near $10 M_{\odot}$, corresponding to a main sequence star of at least 25 - 30 M_{\odot} , but there are production channels that involve appreciably lighter single stars (Woosley and Heger, 2005).

There are also binary channels for making long soft GRBs including a) the merger, by common envelope, of two massive stars, both of which are burning helium in their centers (Fryer and Heger, 2005); b) the merger of a black hole with the helium core of a massive star (Fryer and Woosley, 1998; Zhang and Fryer, 2001); or c) the merger of a black hole and a white dwarf (Fryer et al., 1999b). If the common envelope is completely dispersed and the mass of the merged helium core is $\sim 10 M_{\odot}$ or more, model a) gives a resulting Wolf-Rayet star similar to the single star models. Cases b) and c) result in black hole accretion with higher angular momentum and produce longer bursts, probably longer than typical GRBs. The white dwarf merger model would not give a supernova like SN 1998bw or 2003dh and might not give the observed degree of concentration of GRBs in star-forming regions.

3.3.2 Rotation

The role of rotation in ordinary SNe has long been debated (Hoyle, 1946; Fowler and Hoyle, 1964; Leblanc and Wilson, 1970; Ostriker and Gunn, 1971). GRBs aside, current models assign a role ranging from dominant (Akiyama et al., 2003; Wheeler et al., 2005; Ardeljan et al., 2005), to important (Thompson et al., 2005), and unimportant (Fryer and Warren, 2002, 2004; Scheck et al., 2004). No such ambiguity surrounds the role of rotation in making GRBs. It is crucial in all current models (§ 3.2).

Attempts to model the evolution of angular momentum in massive stars to the point where their iron cores become unstable to collapse have yielded uncertain results. There is general agreement that the omission of magnetic torques leads to cores that do indeed rotate rapidly enough to make a GRB (Heger et al., 2000; Hirschi et al., 2004). Indeed, one could easily end up with the converse problem - too great a fraction of massive stars would make GRBs. However, incorporation of approximate magnetic torques (Spruit, 2002) in single stars that evolve through a red giant phase gives too little rotation for GRBs (Heger et al., 2005), though just about the right amount for pulsars (Ott et al., 2005). This suggests either that the estimated torques are wrong or that special circumstances are required to make a GRB.

Recently, Woosley and Heger (2005) and Yoon and Langer (2005) have discussed the possibility that single massive stars on the high velocity tail of the rotational velocity distribution function might experience “homogeneous evolution” (Maeder, 1987), bypassing red giant formation altogether. Such stars can die with very rapid rotation rates and large core masses but only if the metallicity is low.

The possibility that GRBs are a consequence of binary evolution is frequently discussed (Smartt et al., 2002; Podsiadlowski et al., 2004; Tutukov and Cherepashchuk,

2003, 2004; Fryer and Heger, 2005; Petrovic et al., 2005), but the same caveats apply. Unless the merger occurs well into helium burning, stars with solar metallicity end up with iron cores that rotate too slowly to make GRBs if the estimated magnetic torques are applied (Petrovic et al., 2005; Woosley and Heger, 2005).

In general, the rotation rate for WR stars is not well determined observationally, but is expected, on theoretical grounds, to be rapid, at least for low metallicity (Meynet and Maeder, 2005)

3.3.3 Metallicity

Both the mass and rotation rate of potential GRB progenitors are strongly influenced by mass loss. Expansion of deeper layers to replenish what has been lost from the stellar surface causes them to rotate more slowly and ultimately this torque is communicated to the core. Mass loss also makes the star lighter and easier to explode, hence no black hole. Thus if one wants a GRB, it is helpful if the mass loss rate, especially during the WR phase of the evolution leading up to the GRB, is small. WR stars of low metallicity are known to have smaller mass loss rates (Vink and de Koter, 2005), scaling approximately as $Z^{0.86}$ down to metallicities of 1% solar (where Z refers here to the primordial iron abundance, not the abundances of carbon and oxygen on the surfaces of WC and WO stars). GRBs will therefore be favored in regions of low metallicity (MacFadyen and Woosley, 1999) as has been observed in several cases (Fynbo et al., 2003; Prochaska et al., 2004b; Gorosabel et al., 2005b; Sollerman et al., 2005). Reducing the metallicity to below 10% solar will therefore possibly increase both the frequency and violence of the outbursts. In the collapsar model, more stars will make black holes and those holes will accrete more matter. In the magnetar model, more rapidly rotating neutron stars will be made. This does not preclude the possibility of GRBs in solar metallicity stars by some rare channel of binary evolution, or the estimates of magnetic torques used in the stellar evolution models may be too big.

3.3.4 Frequency

Madau et al. (1998) estimate that the core-collapse rate of all massive stars from redshift 1 to 4 amounts to an observed event rate of 20 per 4 arc minute square on the sky. Over the full sky this corresponds to about 5 SNe per second, a number that should approximately characterize the observable universe. GRBs on the other are thought to occur throughout the universe at a rate of about 3 per day (ref). Correcting for an average factor of 300 in beaming, this means that, universe-wide, the GRB rate is only about 0.2% of the supernova rate. Even allowing for a large number of events in which a GRB-like central engine might produce a supernova or an X-Ray flash without a bright GRB, this suggests that GRBs are a rare branch of stellar evolution requiring unusual conditions. If, however, the GRB rate is strongly metallicity sensitive this fraction might increase with redshift. This is consistent with observations that restrict the GRB rate to be no greater than about 1% the rate of core collapse supernovae (Gal-Yam et al., 2006).

3.4 MODEL DIAGNOSTICS

3.4.1 The Supernova Light Curve and Properties

The fact that bright supernovae sometimes accompany GRBs offers a powerful insight into the explosion mechanism. Type I supernovae of all sorts are believed to be powered, at peak, by the decay of radioactive ^{56}Ni , and its daughter ^{56}Co to ^{56}Fe . ^{56}Ni is only made when matter with near neutron-proton equality (e.g., ^{28}Si , ^{16}O , etc.) is heated to high temperature ($\gtrsim 4 \times 10^9$ K). These high temperatures and the 6.077 day half-life of ^{56}Ni require that it be made in the explosion, not long before. Neither merging neutron stars nor supernovae with a long delay are able to do this.

In a spherically symmetric explosion, the production of ^{56}Ni is limited by the amount of ejected matter interior to a radius given by $4/3\pi r^3 a (4 \times 10^9)^4 E_{\text{exp}}$ where E_{exp} is 10^{51} erg in an ordinary supernova, and perhaps 10^{52} erg in a GRB supernova. To make the $0.5 M_{\odot}$ of ^{56}Ni inferred from some explosions, 10^{52} erg must therefore be deposited in a time equal to that required by the shock to go 10,000 km. Typical supernova shocks at this radius move faster than 10,000 km s^{-1} , so the energy source must radiate a power of $\sim 10^{52}$ erg s^{-1} during the first second of the explosion. This is far more power, at least during the first second, than is required to make the GRB itself.

The GRB jet itself is relatively inefficient at making ^{56}Ni itself if it starts out with a small solid angle. This is both because a small amount of matter is intercepted by the jet and because at very high explosion energies the rapid expansion results in the production of α -particles, not just ^{56}Ni . Still, one expects the distribution of ^{56}Ni in the ejecta to be very asymmetric and concentrated along the rotational axis. Since a GRB observer is also situated along this same axis, high velocities and large blue shifts should be seen. The ^{56}Ni may be rapidly mixed far out in the explosion making it brighter, early on, than a more spherically symmetric explosion. The deformation may also make the supernova light mildly polarized.

An important issue is whether the amount of ^{56}Ni and the expansion rate are likely to be the same in all supernovae with GRBs and XRFs, i.e., is the supernova a standard candle? Despite the similarities between SN 2003dh and SN 1998bw (§2.1.6), the answer probably is “no”. One expects a large variation in the masses and rotation rates of the progenitor stars, especially when metallicity effects are folded in. Different stars will give different rotation rates to their neutron cores, accrete different amounts of mass into black holes of varying sizes, present different density structures to the outgoing blast, etc. Supernovae expanding at a slower rate will be fainter, even if they make the same amount of ^{56}Ni because their light will peak later after more decay and adiabatic degradation. A “supernova” more than 10 times fainter than SN 1998bw would be surprising, especially in the collapsar model, which needs to accrete about a solar mass just to get the jet out of the star. But it still might be explained either by pulsar models or collapsars in which most of the energy came from black hole rotation instead of disk accretion. On the other hand, a supernova more than twice as bright as SN 1998bw would also be surprising. Excepting pair instability supernovae, no such large ^{56}Ni mass has ever been verified in any supernova and it is probable that a collapsar with such a vigorous wind would shut off its own accretion. These limits are consistent with the observed spread in supernova luminosities in XRFs

(Soderberg et al., 2005).

3.4.2 Unusual Supernovae and Transition Objects

Supernovae are visible at all angles, last a long time, and do not require relativistic mass ejection. There could therefore be a large number of “orphan” supernovae in which the same central engine acts, but which, for some reason, does not give an observable GRB. Perhaps the jet had too much baryon loading or died prematurely. Perhaps a GRB went off in another direction, or, for 20 seconds, we simply were not looking at the right place. Still the fraction of all supernovae with the unusual characteristics of GRB-SNe is small (§ 3.3.4). It is also much easier to see the GRB from a great distance, hence many GRB-SNe go undetected. A volume limited sample of GRBs and broad line, Type I supernovae would give interesting constraints on the beaming and jet break out, but so far the data is too limited.

Specific cases include Type Ic supernovae SN 1997ef, 1997dq (Mazzali et al., 2004) and SN 2002ap (Mazzali et al., 2002; Yoshii et al., 2003). All show evidence for peculiarity and high energy. Despite high velocity, a photosphere persists until late times. SN 2003jd, also a Type Ic, shows evidence for two components of oxygen, one at high velocity, one at low (Mazzali et al., 2005). These observations are best explained in a two component model (Maeda et al., 2003; Woosley and Heger, 2003) in which the the supernova has a high velocity along its rotational axes, reflecting the activity of some jet-like energy source, and low velocities in the equator.

Perhaps the clearest case so far of a transition supernova is SN 2005bf, (Maeda et al., 2005; Tominaga et al., 2005; Folatelli et al., 2005), a supernova that a) contained broad lines of Fe II and Ca II, but only a trace of hydrogen, b) had two distinct velocity components, and c) had two luminosity peaks, the second being almost as bright as a Ia but occurring 40 days after the explosion. No spherically symmetric model with a monotonically declining distribution of ^{56}Ni is capable of explaining the observations. The explosion had to be an exceptionally massive helium core to peak so late and yet make an unusually large amount of ^{56}Ni to be so bright then. The explosion energy was also well over 10^{51} erg. But the spectrum did not resemble so much that of SN 1998bw as an ordinary Ib or Ic supernova.

All these supernovae so far are the explosion of WR stars of one sort or another. It is expected on theoretical grounds that stripped down helium cores will retain a higher angular momentum than those embedded in red giant envelopes (§ 3.3.2). Also, the asymmetry of the explosion tends to be damped out in stars with extended envelopes (Wang et al., 2001) and the high velocities in the helium core are tamped. Still hyperactivity has been reported in Type II supernovae. SN 1997cy (Germany et al., 2000), the brightest supernova ever and a Type II, was possibly associated with short hard burst GRB 970514. However with 4 month’s uncertainty in the explosion date and difficulty making short hard bursts in massive stars, this association is probably coincidental. The high luminosity, attributed by Germany et al to $2.6 M_{\odot}$ of ^{56}Ni , may have been due to circumstellar interaction (Turatto et al., 2000). Similar caveats apply to the identification of Type II SN 1999E with GRB 980910 (Rigon et al., 2003)

3.4.3 Energetics

As was discussed in § 2.4, the energy budget of a GRB-SN can be broadly partitioned according to the Lorentz factor of its ejecta. The supernova itself, as determined by its spectral line widths, its nucleosynthesis, and some estimate of its mass, is a measure of the non-relativistic ($1 < \Gamma < 1.005$) kinetic energy, E_{SN} . The afterglow measures the energy in $\beta\Gamma \gtrsim 2$ ejecta, E_{Rel} , and the GRB measures the energy of matter with $\Gamma \gtrsim 200$, E_{GRB} . In general, one expects $E_{SN} > E_{Rel}$ and by definition, $E_{Rel} > E_{GRB}$, but there is no reason that the ratio, E_{SN}/E_{Rel} , should be a constant from event to event, and it probably isn't (Malesani et al., 2004a; Soderberg et al., 2004b).

In the collapsar model, E_{SN}/E_{Rel} measures the energy in the disk wind compared to that in the jet. In the pulsar model, it measures the ratio of prompt large-angle energy input to late time input with small angles. In both cases, the answer could vary with accretion rate, angular momentum, magnetic field strength, and stellar mass. Conversely, observations of this ratio will ultimately constrain these uncertainties in the models.

3.4.4 Optical Spectroscopy of the Afterglow

As light from the GRB and, later, the supernova passes through the wind of the progenitor star, distinctive lines may be created that are informative of the star's mass loss rate, wind speed, and composition (Schaefer et al., 2003; Mirabal et al., 2003; van Marle et al., 2005). Multiple components are seen with speeds ~ 500 km s⁻¹ and ~ 3000 km s⁻¹. The highest velocity lines probably originate near the progenitor and reflect the WR wind speed when it died, but lower speed lines are produced by a nebula farther out that is either the fractured residual of a collision between the WR wind and a previous red supergiant wind or radiatively accelerated by the burst. Observations so far are consistent with the wind of a WR star, perhaps of class WC, but constrain the lifetime of the WR progenitor to be shorter than expected (van Marle et al., 2005).

Some have suggested an origin as due to radiative acceleration of dense clumpy nebular material by the GRB afterglow (Mirabal et al., 2002; Schaefer et al., 2003; Ramirez-Ruiz et al., 2005). Then the absence of detectable photoionization or deceleration places constraints on the circumburst radii of the absorbing material (Mirabal et al., 2002; Schaefer et al., 2003) and possible companions to the progenitor (Starling et al., 2005; Fiore et al., 2005). Other (less locally based) origins are possible, such as SNe remnants (Lazzati et al., 2002), quasar absorption systems (Mirabal et al., 2002), or galactic superwinds. Given the alternatives, and since only a handful of GRBs have exhibited such blueshifted absorption, absorption spectroscopy has yet to establish a definitive connection with the circumburst environment. Still, with more frequent spectroscopic observations at early times after a GRB, there is hope that the measurement of time-dependent metal columns and velocities could provide important diagnostics of the progenitors.

3.4.5 X-Ray Lines

X-ray lines are potentially a powerful diagnostic of the supernova-GRB combination. Lines from various elements have been reported in the afterglows of at least seven GRBs using a variety of instruments (e.g., Piro et al., 2000; Reeves et al.,

2002; Piran, 2005, and references therein). They are sometimes seen in emission about 10 hours after the burst with a luminosity of $10^{44} - 10^{45}$ erg s^{-1} for at least several hours. Typically the lines are Fe-K α , though the K α lines of Si, S, Ar, and Ca have also been reported. Unfortunately, the statistical significance of these signals is not universally accepted (Rutledge and Sako, 2003). If real, the lines might be expected in the supranova model, though other alternatives have been discussed (Mészáros and Rees, 2001; Kumar and Narayan, 2003; Kallman et al., 2003) in which the supernova and GRB are simultaneous.

3.4.6 GRB-SNe Remnants

The supernovae that accompany GRBs may be hyper-energetic compared with ordinary supernovae and are certainly accompanied by jets. These peculiarities might manifest themselves in the remnant a long time after the explosion is over. However, the jet energy is probably less than the supernova energy, and initial asymmetries are eroded once the explosion has swept up several times the initial mass of the progenitor star. Ayal and Piran (2001) estimate a time ~ 5000 years for this to occur, and, given the low event rate for GRBs, estimate a remnant population ~ 0.05 per galaxy. On the other hand, Perna et al. (2000) and Roberts et al. (2003) discuss unusual SNR's that may have involved unusual energy or asymmetry. These observations may have other explanations though - e.g., multiple supernovae.

3.4.7 Compact Remnants

The black hole left in the collapsar model would be very rapidly rotating (Kerr parameter ~ 1), but the spin of an isolated black hole is unobservable from far away. If the GRB occurred in a binary system that somehow remained bound (admittedly a big *if*) and later became an accreting x-ray source (Brown et al., 2000), measurement of the mass and Kerr parameter (Middleton et al., 2006; Shafee et al., 2006; Psaltis, 2004) of the black hole would both show large values. Indeed, measurements of Kerr parameters in the range 0.5 to 1, even for black holes that may *not* have made GRBs, but do not seem to have been spun up by later accretion, would strongly suggest that rotation is an important component of some supernovae.

The object left in the millisecond magnetar model would be a very magnetic neutron star ($B \sim 10^{15}$ G), with a still rapid rotation rate and high luminosity, though probably not visible unless the burst were relatively nearby. This would essentially be the birth of a magnetar. Since the magnetic activity of such objects has been associated with soft gamma-ray repeaters (e.g., Woods and Thompson, 2005) and since SGR activity might possibly be visible out to a distance of 70 Mpc (Tanvir et al., 2005), nearby GRB sites, specifically that of GRB 980425 at 40 Mpc, might be monitored for repeated bursting activity.

3.4.8 Nucleosynthesis

Pruet et al. (2004b) and Surman and McLaughlin (2005) find that the nucleosynthesis in the disk wind of collapsars consists mostly of ^{56}Ni for the relevant range of accretion rates. The winds do not preserve the large neutron excess characteristic of the inner disk because the outgoing nucleons capture electron-positron pairs and neutrinos. If “bubbles” remove disk material at an unusually

low density and rapid rate, heavier nuclei can be produced, even the r -process, but this is highly uncertain.

In the ideal case GRBs would greatly overproduce one or more nuclear species not made elsewhere. Pruet et al. (2004a) have found that the wind from collapsar disks can synthesize interesting large abundances of ^{42}Ca , ^{45}Sc , $^{46,49}\text{Ti}$, and ^{63}Cu , but these same species can be produced in ordinary supernovae (Woosley et al., 2002)

3.4.9 Afterglows and Density Gradients

The afterglow of a GRB in radio and x-ray is generally regarded as coming from the external shock of the GRB producing jet as it decelerates in the external medium. Breaks in the light curves of this emission can yield information on the opening angle of the jet and therefore on the actual total relativistic energy in the event (Frail et al., 2001; Piran et al., 2001; Panaitescu and Kumar, 2002). In addition, the afterglow offers unique insight into the mass loss history of the star just before it exploded. If the metallicity is low, one expects mass loss rates much smaller than for typical WR stars in our galaxy (§ 3.3.3).

It is important to note that radio emission from GRBs and Type Ibc supernovae samples the mass loss during an epoch of stellar evolution that is otherwise unobserved (and therefore not tightly constrained). During the last several hundred years of their lives WR stars over $8 M_{\odot}$ are burning carbon and heavier elements in their cores (Woosley et al., 2002). For a wind speed of 10^8 cm s^{-1} , this mass loss determines the distribution of mass out to 10^{18} cm wherein all the afterglow is formed. The mass inside 10^{15} cm , where the burst itself gets made, reflects the last few months in the star's life when it was burning oxygen and silicon. So long as the mass loss rate depends only on the surface luminosity of the star, it will not change much, for a WR star of given mass and metallicity, from helium burning until explosion. The luminosity varies by only about 50%. But if these late stages are pulsationally unstable with a short growth time, the mass loss could be quite different - perhaps higher. The mass loss of WR-stars is also known to be clumpy (Hamann and Koesterke, 1998), and that could complicate the modeling.

In general, though, unless the mass loss is rapidly varying, which seems doubtful in carbon burning, the density should scale as r^{-2} . This scaling is consistent with radio observations of some GRBs (Chevalier and Li, 2000; Li and Chevalier, 2001; Panaitescu and Kumar, 2002; Price et al., 2002; Greiner et al., 2003b), but inconsiderate with others (Chevalier and Li, 1999; Kumar and Panaitescu, 2003). The latter is difficult to reconcile with the otherwise successful paradigm that long soft GRBs originate from the deaths of massive stars, but the complex interplay between the winds and the interstellar medium could mask global wind signatures and even mimic a constant density environment (Wijers, 2001; Chevalier et al., 2004; Ramirez-Ruiz et al., 2005).

3.4.10 Gravitational Radiation and Neutrinos

All models produce compact objects and require a lot of rotation and thus predict a gravitational radiation signature of some sort (Fryer et al., 2001; Davies et al., 2002; Kobayashi and Mészáros, 2003; van Putten et al., 2004a,b). However, most of the models are cylindrically symmetric. Perhaps the best opportunity would

be from the initial collapse that leads to the collapsar. The proto-neutron star has more angular momentum than even a neutron star rotating at break up and thus might pass through a highly deformed stage before collapsing to a black hole (Baumgarte et al., 2000). But the cylindrically symmetric exclusion of the excess angular momentum in a disk is also a possibility that could greatly diminish the gravitational radiation.

The neutrino burst from core collapse is not much brighter than in ordinary supernovae and may even be fainter. Given the large distances and soft spectrum, these neutrinos are probably not visible above the background. However, very energetic neutrinos can be produced by a relativistic jet traversing a massive star (Mészáros and Waxman, 2001; Razzaque et al., 2004, 2005).

4 THE FUTURE - A MYSTERY UNSOLVED

While the observations of the last seven years have revealed an exciting link between supernovae and the long-soft GRBs, it would be premature to think that we understand either one of them very well. No complete physical model currently exists for even the most common variety of supernova. Indeed, one of the most important consequences of the SN-GRB connection may be a better understanding of how massive stars die.

Some specific diagnostics that might help with this were given in § 3.4. Here we mention a few places where we think significant progress could happen in the next decade. Some progress will come simply from a larger sample of GRB-SN and from codes of increased realism running on more powerful computers. Other advances may require the development of space missions beyond Swift and ground-based facilities that are only now in the planning stages. We restrict our list to science specifically related to the SN-GRB connection, not everything we want to know about, or can do with GRBs.

- How variable — in energy, mass, and luminosity — is the class of supernovae that accompany XRFs and GRBs? We have taken the position here that all of these high energy transients, except perhaps the short bursts, are accompanied by stellar explosions of some sort. Is that true? Were SN 1998bw and SN 2003dh unusually bright? Are there any systematic differences in the supernovae that accompany long-soft GRBs of different duration, energy, spectral hardness, etc.?
- Are GRBs favored by low metallicity? Do the average properties of GRBs vary significantly (in their rest frame) with redshift? Since mass loss decreases with metallicity, GRBs from high redshift might preferentially come from more massive and more rapidly rotating stars. This might reflect in the properties of the bursts and their afterglows.
- Pushing this to the extreme, can we use GRBs to study Population III stars at very high redshift, including stars of much higher mass than die as supernovae today? Bursts from redshift 10 – 20 would be both highly time dilated and severely reddened. A new mission or mission strategy may be necessary that combines observations in the infrared and hard x-ray.
- What is the most common form of GRB in the universe? It is possible that observations so far have been selectively biased to more luminous events. Are events like GRB 980425 actually more frequent than “ordinary” GRBs?

More sensitive studies over a long period could eventually give, at least, a volume-limited local sample.

- What is the relation between XRFs and GRBs? Are XRFs the result of GRBs seen off axis, the result of jets that have lower Lorentz factors at all angles, or something else? Observationally, it will be important to see if the distribution of properties of XRFs and GRBs is continuous from one extreme to the other. Theoretical models are still primitive. Are both phenomena due to internal shocks or is a mixture of internal and external shocks involved?
- Similarly, is there a continuum of events between core collapse supernovae and GRBs, or are they two discrete classes of phenomena? Rapid differential rotation in the core of a massive star when it dies has been implicated as a necessary ingredient for GRBs. Rotation may play a role in producing all manner of unusual supernovae like those mentioned in § 3.4.2, even those that have no GRBs. But is it important in ordinary Type IIp supernovae?
- How is the jet launched in a long soft GRB? Is the jet a fireball or Poynting flux? This is largely an ongoing issue for theory and simulation with important implications for active galactic nuclei and pulsars as well as GRBs. There may be observational diagnostics, however, in the polarization of afterglows and the strength of the optical afterglow.
- How long does the central engine operate? Is its power at late times continuous or episodic? Recent studies with Swift have shown some evidence in some bursts for substantial energy input continuing long after the main burst is over. Variable late time energy input could be a consequence of incomplete ejection of all mass in the supernova which leads to continued accretion in the collapsar model, though pulsar-based explanations are not ruled out.
- Do supernova-like displays ever occur with short hard bursts? Present data suggest that they do not, but the exceptions should continue to be sought.
- In the longer time frame, neutrino bursts and gravitational radiation may possibly yield the greatest insight into the nature and activity of the central engine, since it is only in these emissions that the central engine is directly observable.

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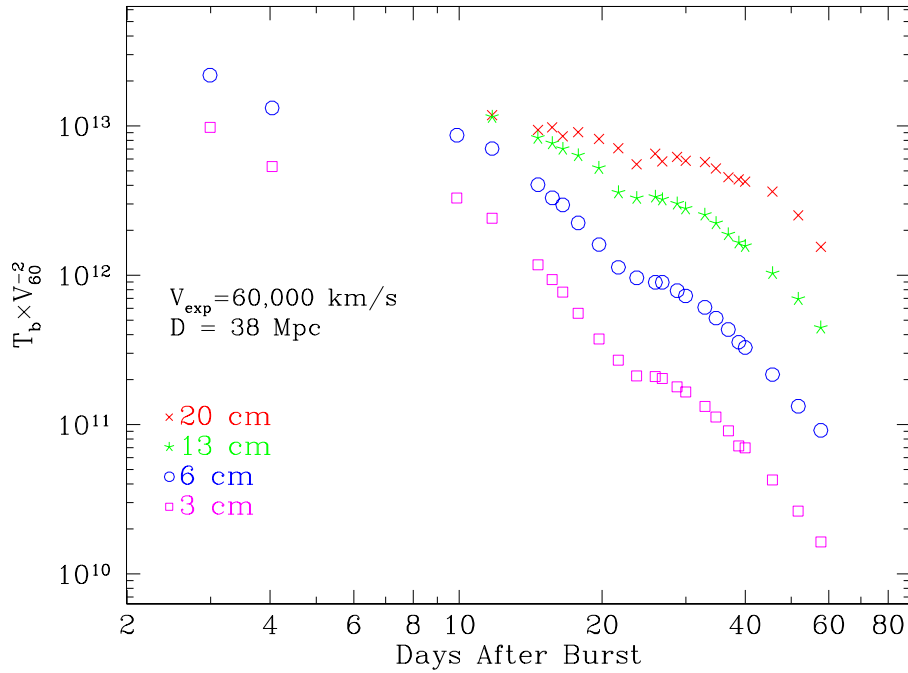


Figure 1: The evolution of the brightness temperature of radio SN 1998bw, the most luminous RSN ever recorded. The brightness temperature is computed under the assumption that the radio photosphere expanded with the same velocity inferred from optical spectroscopy ($\sim 0.2c$). In order for the true brightness temperature to be less than the “Compton Catastrophe” value ($T_{CC} \approx 10^{12}$ K), relativistic motion in the first week after 980425 is required. From Kulkarni et al. (1998)

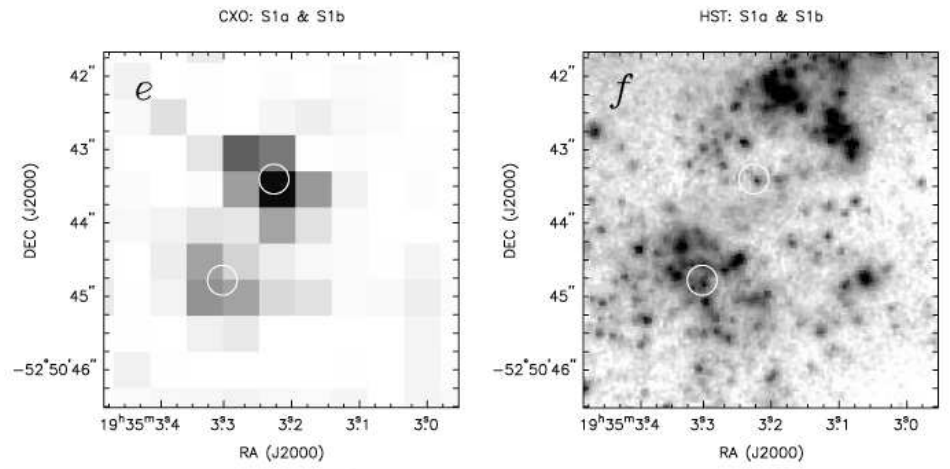


Figure 2: The location of SN 1998bw as viewed at late times by *Chandra* (left) and *HST* (right). The circles represent the 1σ astrometric position from *Chandra*. The fading X-ray source (“S1a”) consistent with SN 1998bw is to the south east (bottom left). From Kouveliotou et al. (2004)

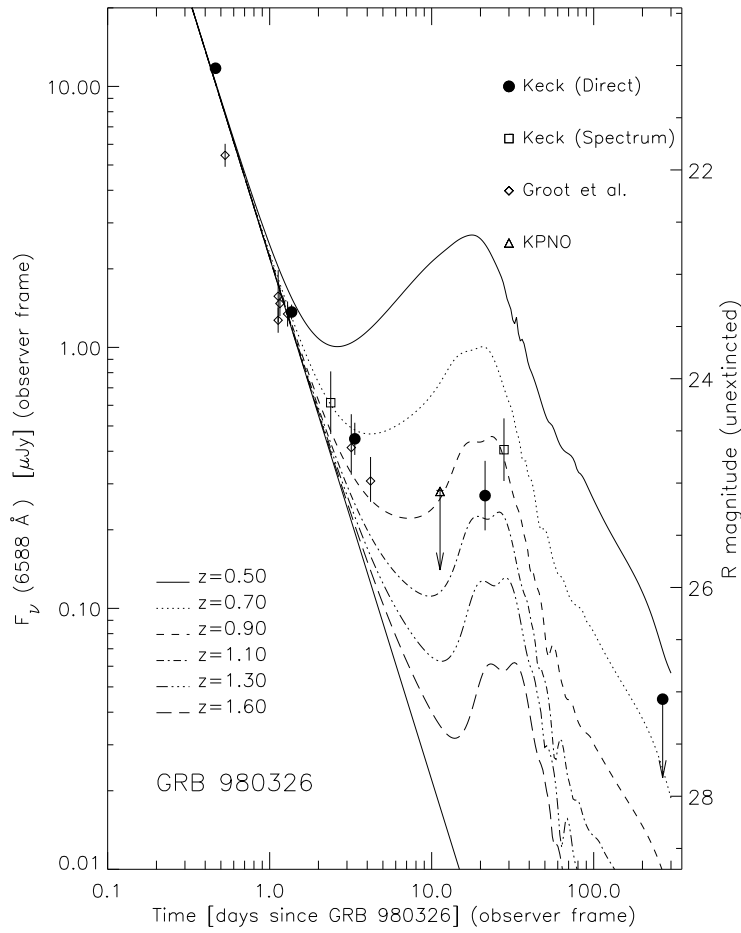


Figure 3: An optical SN-like bump superimposed on the afterglow of GRB 980326. Models of SN 1998bw at different redshifts are shown. The color and light curve of the bump was found to be consistent with 1998bw at redshift of unity. Without a measured redshift, however, there is a degeneracy between the absolute brightness, distance, and extinction due to dust in the host galaxy. From Bloom et al. (1999a).

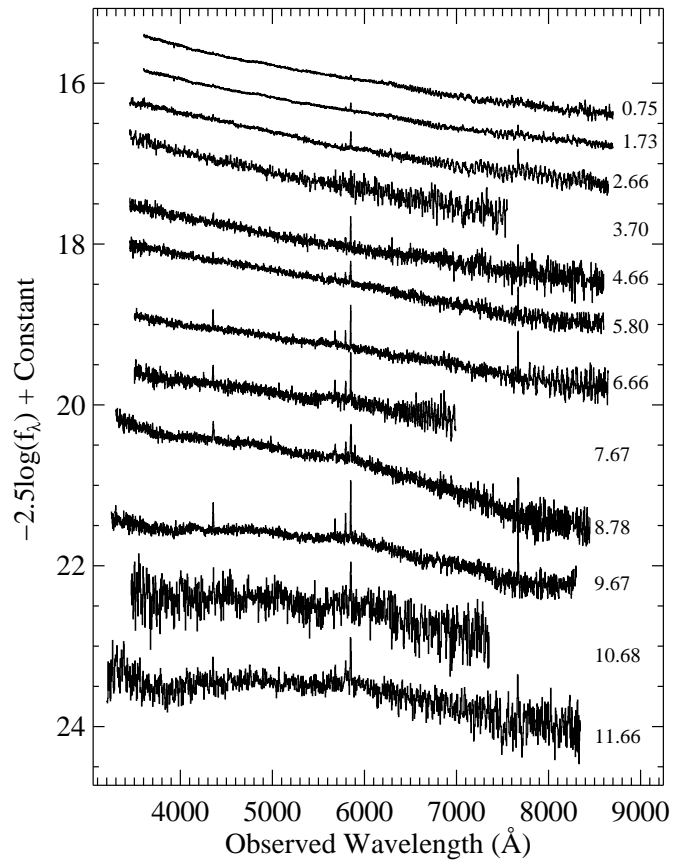


Figure 4: The discovery spectra of the emergence of SN 2003dh from the glare of the afterglow of GRB 030329. Shown is the observed spectra, a combination of afterglow and supernova. Days since the GRB are noted at right. The narrow emission lines are from the host galaxy and do not change in intensity throughout. From Matheson (2004).

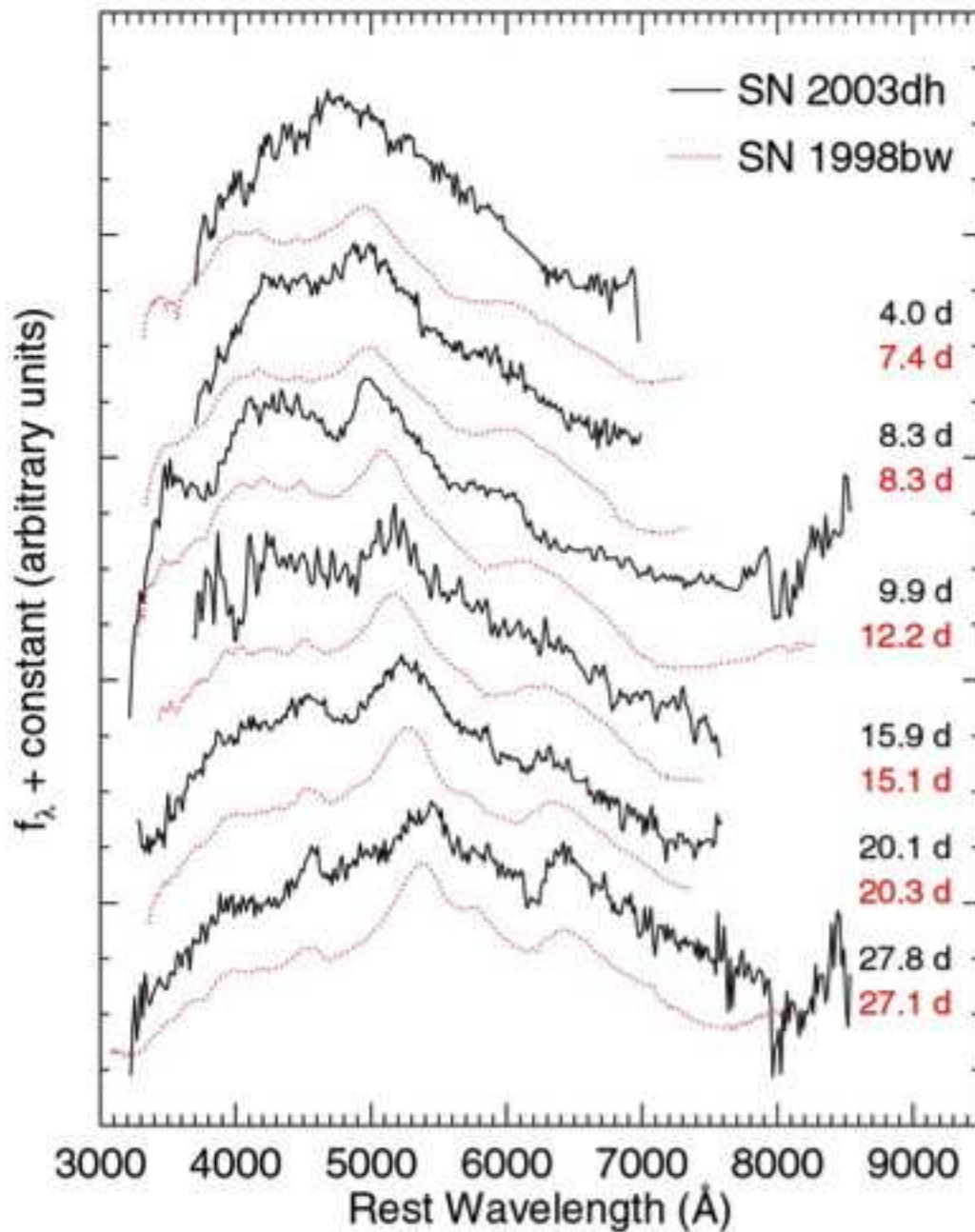


Figure 5: A comparison of the rest frame optical spectrum of SN 1998bw and SN 2003dh (associated with GRB 030329). The spectral features and evolution show a remarkable similarity suggesting that the SN explosions of cosmological GRBs are connected to the mechanisms inferred for 1998bw. The afterglow component has been modeled and removed from the observed spectra. From Hjorth et al. (2003)

Table 1: Properties of good candidate supernovae associated with GRBs, X-Ray Flashes, and X-Ray Rich GRBs

Name Burst/SN	z	Peak [mag]	T_{peak}^a [day]	SN likeness/ designation	References
GRB 980425/1998bw	0.0085	$M_V = -19.16 \pm 0.05$	17	Ic-BL	b
GRB 030329/2003dh	0.1685	$M_V = -18.8$ to -19.6	10 - 13	Ic-BL	c
GRB 031203/2003lw	0.1005	$M_V = -19.0$ to -19.7	18 - 25	Ibc-BL	d
XRF 020903	0.25	$M_V = -18.6 \pm 0.5$	~ 15	Ic-BL	e
GRB 011121/2001dk	0.365	$M_V = -18.5$ to -19.6	12 - 14	I (IIn?)	f
GRB 050525a	0.606	$M_V \approx -18.8$	12	I	g
GRB 021211/2002lt	1.00	$M_U = -18.4$ to -19.2	~ 14	Ic	h
GRB 970228	0.695	$M_V \sim -19.2$	~ 17	I	i
XRR 041006	0.716	$M_V = -18.8$ to -19.5	16 - 20	I	j
XRR 040924	0.859	$M_V = -17.6$	~ 11	?	k
GRB 020405	0.695	$M_V \sim -18.7$	~ 17	I	l

^aThe time of peak brightness is reported in the rest frame if the redshift is known, observed frame otherwise. ^bGalama et al. (1998). ^cHjorth et al. (2003); Stanek et al. (2003); Bloom et al. (2004); Lipkin et al. (2004). ^dMalesani et al. (2004a); Cobb et al. (2004); Thomsen et al. (2004); Gal-Yam et al. (2004). ^eSoderberg et al. (2005). ^fBloom et al. (2002b); Garnavich et al. (2003b); Greiner et al. (2003b). ^gDella Valle et al. (2006). ^hDella Valle et al. (2004). ⁱGalama et al. (2000); Reichart (1999). ^jStanek et al. (2005); Soderberg et al. (2006b). ^kSoderberg et al. (2006b). ^lPrice et al. (2003).

Table 2: Physical Properties of GRB-SNe

GRB/SN	E_{SN} (10^{52} erg)	E_{Rel} (10^{49} erg)	$E_{\text{iso}}(\gamma)$ (10^{49} erg)	E_{γ} (10^{49} erg)	$M(^{56}\text{Ni})$ (M_{\odot})	Refs.
980425/1998bw	2 - 3 ^a	1 - 30	0.06 - 0.08	<0.08	0.5 - 0.7	b
030329/2003dh	2 - 5	≈ 50	1070	7 - 46	0.3 - 0.55	c
031203/2003lw	2 - 3	2	2.94 ± 0.11	<3	0.5 - 0.7	d

^aHöflich et al. (1999) inferred a kinetic energy for SN 1998bw one order of magnitude smaller based upon highly asymmetric model.

^bIwamoto et al. (1998); Woosley et al. (1999); Li and Chevalier (1999); Galama et al. (1998); Friedman and Bloom (2005)

^cMazzali et al. (2003); Berger et al. (2003c); Woosley and Heger (2005); Deng et al. (2005); Frail et al. (2005); Friedman and Bloom (2005)

^dMalesani et al. (2004b); Gal-Yam et al. (2004); Lipkin et al. (2004); Soderberg et al. (2004b); Sazonov et al. (2004); Friedman and Bloom (2005)

^eThe absence of increasing energy inferred in the afterglow blast wave at late times, suggests that these sources were not off-axis GRBs (e.g., Soderberg et al., 2004b) and therefore that $E_{\text{iso}}(\gamma)$ is indeed an upper limit to the true energy released in γ -rays.

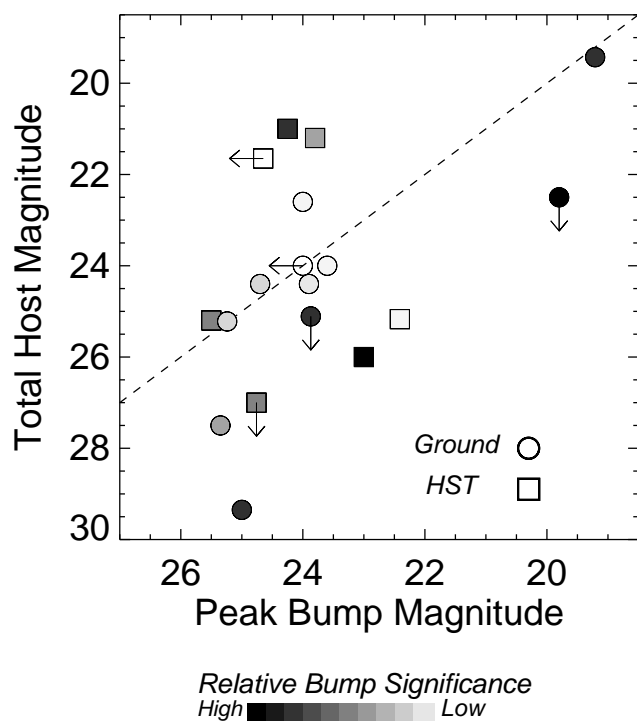


Figure 6: Illustration of the difficulty in finding GRB-SNe: claimed bump peak magnitudes versus the integrated magnitude of the host galaxy. Relative significances of the detections are based on our subjective analysis of the believability of the bumps. Many bumps were claimed by differencing catalog magnitudes — small systematic errors in measuring the true host magnitudes artificially reveal bumps. High resolution imaging ameliorates some of the endemic problems of bump detections from catalogs.

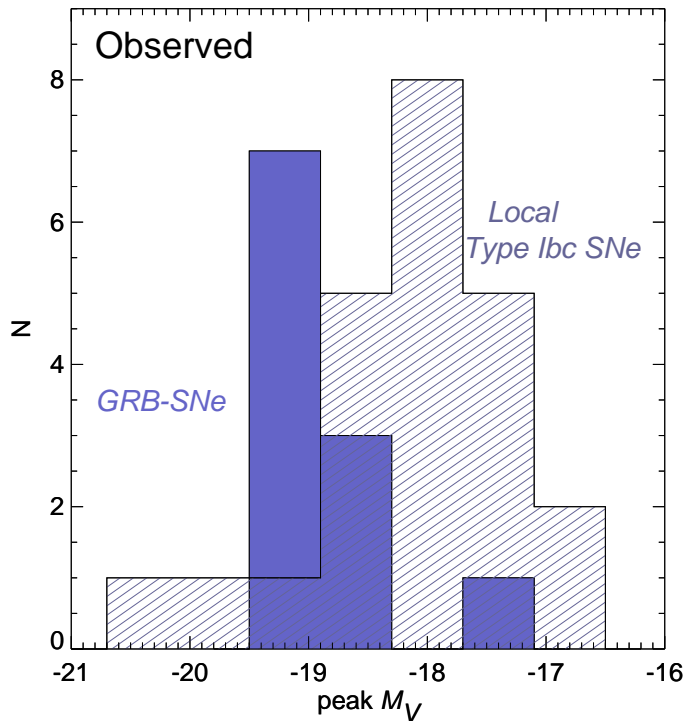
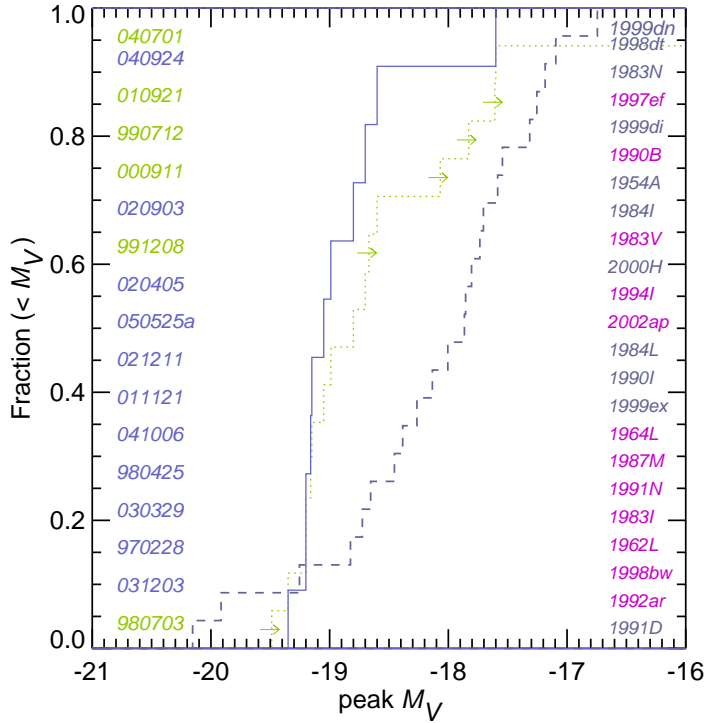


Figure 7: Comparison of the peak M_V of GRB-SNe to the local Ibc population. (Top) Cumulative distribution of the Ibc SNe from Richardson et al. (2006) shown as a dashed line. The distribution of the *observed* GRB-SNe are shown as a solid line; we include SNe from XRFs and XRR GRBs. The dotted line include those GRBs with no significant bump detection or bumps which do not resemble SNe. The names of the associated GRB are shown at left and the names of the Ib (grey) and Ic (mauve) are shown at right. (Bottom) Histogram of the secure bumps as compared to the local Ibc population. GRB-SNe populate the “bright” subclass of the Richardson et al. (2006) sample, but, as we show in the text, the bump

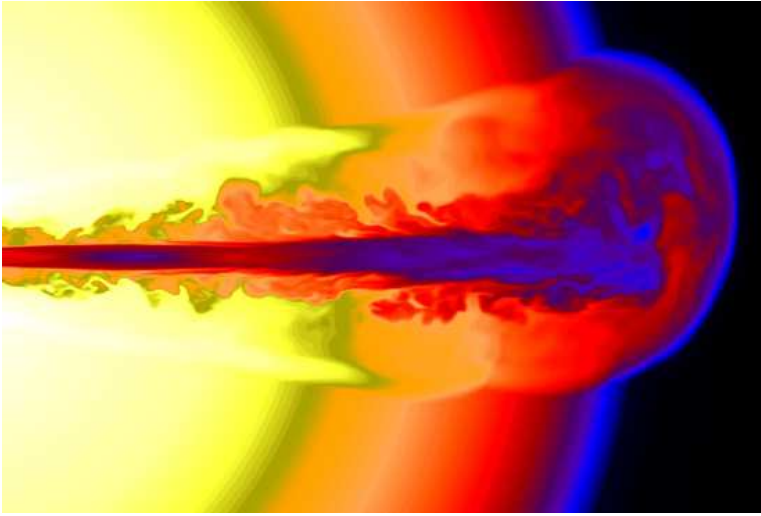


Figure 8: Break out of a relativistic GRB jet with energy 3×10^{50} erg s^{-1} 8 seconds after it is launched from the center of a $15 M_{\odot}$ Wolf-Rayet star. The radius of the star is 8.9×10^{10} cm and the core jet, at infinity, will have a Lorentz factor $\Gamma \sim 200$. Note the cocoon of mildly relativistic material that surrounds the jet and expands to larger angles. Once it has expanded and converted its internal energy this cocoon material will have Lorentz factor $\Gamma \sim 15 - 30$. A off-axis observer may see a softer display dominated by this cocoon ejecta. If the star were larger or the jet stayed on a shorter time, the relativistic core would not emerge, though there would still be a very energetic, highly asymmetric explosion. (Zhang et al., 2004)

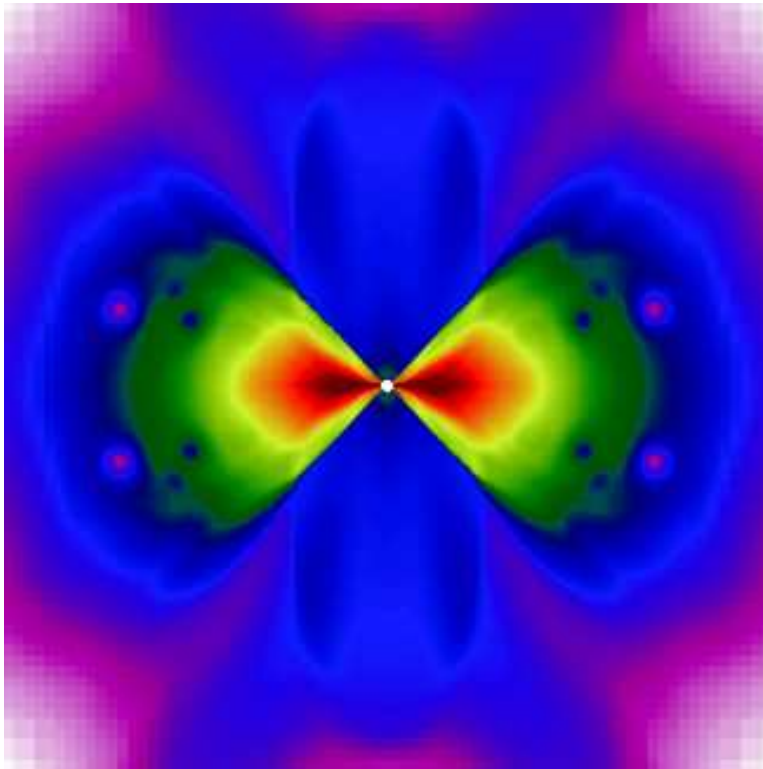


Figure 9: Collapse of the core of a rapidly rotating $14 M_{\odot}$ Wolf-Rayet star. Twenty seconds after collapse, a black hole of $4.4 M_{\odot}$ has formed and has accreted at $\sim 0.1 M_{\odot} s^{-1}$ for the last 15 seconds. The figure is 1800 km across and the inner boundary is at 13 km. Colors indicate density on a logarithmic scale, with the highest density in the equatorial plane near the black hole being $9 \times 10^8 \text{ g cm}^{-3}$. (MacFadyen and Woosley, 1999, Zhang, Woosley, & MacFadyen, in preparation.)

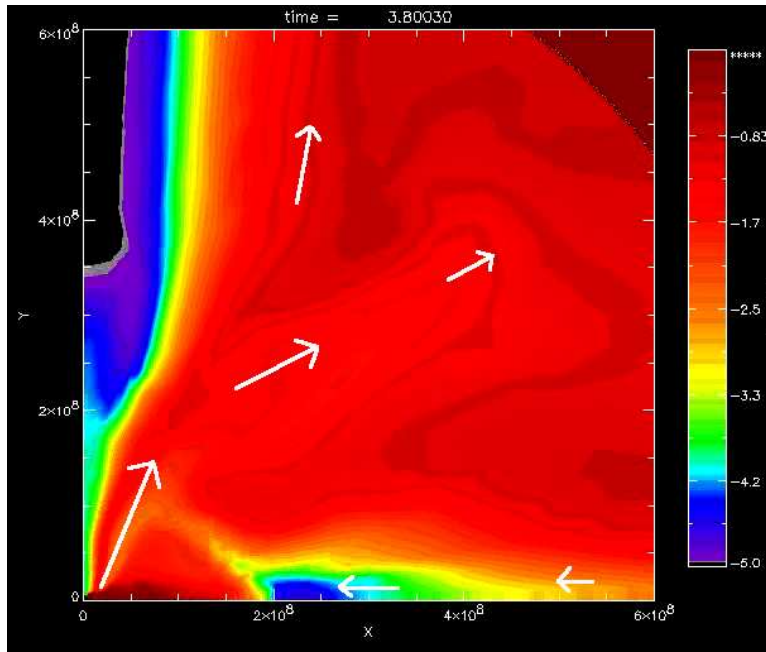


Figure 10: A “wind” of nucleons blows off the black hole accretion disk. In the collapsar model, this wind is responsible both for blowing up the star and producing the ^{56}Ni to make it bright. In this numerical simulation, the action of magnetohydrodynamical instabilities in the disk is represented by a simple “alpha-disk” viscosity ($\alpha \approx 0.3$). The highest wind velocity (long white arrow) is $\sim 20,000 \text{ km s}^{-1}$, and the mass in the wind is a fraction ($\sim 50\%$) of the $0.1 M_{\odot} \text{ s}^{-1}$ accretion rate. Matter flows in at the equator, is photodisintegrated, and ejected as neutrons and protons. Farther out these nucleons cool and assemble to ^{56}Ni . This is a separate phenomenon from the core jet that makes the GRB. The figure is color coded by temperature with the hottest (dark red) region being $\sim 4 \times 10^{10} \text{ K}$. The outer radius of the figure is $6,000 \text{ km}$, so the inner disk of 300 km is the dark part, in the lower left corner. (MacFadyen and Woosley, 1999; MacFadyen, 2003)