What Gamma-Ray Bursts Explode Into

Roger A. Chevalier

Dept. of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904, USA

Abstract

The association of long gamma-ray bursts (GRBs) with Type Ib/c supernovae implies that they explode into the winds of their Wolf-Rayet progenitor stars. Although the evolution of some GRB afterglows is consistent with expansion into a free wind, there is also good evidence for expansion into a constant density medium. The evidence includes the evolution of X-ray afterglows (when X-rays are below the cooling frequency), the evolution of the pre-jet break optical and X-ray afterglow, and the sharp turn-on observed for some afterglows. Recent observations of short bursts, which are expected to be interacting with a constant density medium, provide a check on the standard afterglow model. Although radio observations do not support the constant density model for long bursts in some cases, the evidence for constant density interaction is strong. The most plausible way to produce such a medium around a massive star is to shock the progenitor wind. This requires a smaller termination shock than would be expected, possibly due to a high pressure surroundings, a high progenitor velocity, or the particular evolution leading to a GRB. However, the need for the termination shock near the deceleration radius cannot be plausibly accomodated and may indicate that some long bursts have compact binary progenitors and explode directly into the interstellar medium.

Key words: Gamma-ray bursts, mass loss, supernovae
PACS: 97.10.Me, 97.60.-s, 98.70.Rz

1 Introduction

Observations of the long duration gamma-ray bursts (GRBs), which are the primary topic here, suggest that they are associated with the deaths of massive stars. One line of evidence for this has been their association with supernovae (SNe). Woosley & Bloom (2006) list 11 cases that are good candidates for SNe associated with bursts. However, 2 recent long bursts have shown no evidence for a SN to faint levels (Fynbo et al., 2006). Another line of evidence is the apparent association of the sites of long bursts with regions of active star formation.

Email address: rac5x@virginia.edu (Roger A. Chevalier).

Fruchter et al. (2006) found that the positions of GRBs on galaxies are more concentrated to the brightest pixels than are core collapse supernovae, suggesting that the GRBs are associated with more massive stars than are most core collapse supernovae.

These properties imply that the progenitors of most explosions are Wolf-Rayet (WR) stars. Expectations for the surroundings of WR stars are discussed in Section 2. Normal SNe Ib/c (without a GRB connection) are also expected to interact with the surroundings of WR stars. The properties of the interaction, as observed at radio and X-ray wavelengths, can provide insight into the GRB case (Section 3). The SNe Ib/c that are associated with nearby, low luminosity GRBs distinguish themselves from the normal SNe Ib/c and are discussed in Section 4. Afterglow emission gives us a prime method of determining the surrounding medium and has been used since the discovery of afterglows to infer the density. This issue is examined in the light of recent observations in Section 5. A frequent deduction from the analysis of afterglows is that the surroundings have a constant density. In this paper, GRB is used to refer to the long duration GRBs. The short bursts are discussed in relation to the long bursts in Section 6. Possible ways of producing a constant density surroundings are discussed in Section 7. Absorption lines in optical spectra provide another possible window on the immediate surrounding of GRBs and are treated in Section 8. The various issues related to the surroundings of GRBs are summarized in Section 9.

2 The Surroundings of Wolf-Rayet Stars

In this section, I consider the surrounding medium created by the free wind from a WR star, as it is likely to provide the immediate environment for the GRB. At some point the wind is expected to transition to a region that results from interaction with the surroundings; this possibility will be considered in Section 7. Typical parameters for a WR star wind are a mass loss rate $\dot{M} = 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ and a wind velocity $v_w = 10^3$ km s^{-1}. The wind density $\rho_w = Ar^{-2}$, where $A = \dot{M}/4\pi v_w$, is the critical parameter for a high velocity interaction and I characterize it by $A_* = A/5\times10^{11}$ g cm^{-1} $= (\dot{M}/10^{-5}\ M_\odot\ \mathrm{yr}^{-1})(10^3\ \mathrm{km\ s}^{-1}/v_w)$. For Galactic stars, Nugis & Lamers (2000) listed mass loss parameters for 64 WR stars, yielding an A_* range of 0.07 to 7.4. The lowest density winds are produced by WO stars, because of their high values of v_w, up to 5500 km s^{-1}. These results are based on Nugis et al. (1998), who determined clumping-correcting radio mass loss rates, noting that the effect of clumping is small at the stellar surface, grows to a maximum at $\sim 5-10R_*$, and again becomes small in the outer wind because of the expansion of clumps at the local sound speed.

A difference of the progenitors of GRBs with Galactic WR stars is that the GRB progenitors probably have lower metallicity. Modjaz et al. (2007) found that the nearby GRB/SNe are in regions that are systematically more metal poor than the regions containing core collapse supernovae. Metallicities were determined from emission line regions close to the explosions. The metallicities could be a factor of ~ 6 smaller than solar. For more distant GRBs, it is not clear whether the GRBs have lower metallicities compared to other galaxies at a similar redshift z, but metallicities $Z \sim 0.05 - 0.5\ Z_\odot$ are indicated. In recent years, it has been found that heavy elements around the Fe peak play a role in driving the winds from WR stars, so that their mass loss rates are Z dependent. In this metallicity range, mass loss rates from WC stars vary as $\sim Z^{-0.6}$ (Crowther, 2006), suggesting that values of $\dot{M}$ for GRB progenitor stars are lower than the rates for Galactic WR stars by a factor of $2 - 3$, and the values of A_* are lower by a similar factor.

Another issue is the possible asymmetry of the stellar wind. Polarization studies of Galactic WR stars have generally shown an undetectable amount of polarization, although $\sim 20\%$ show a polarization $\gtrsim 0.3\%$ that can be interpreted as a density contrast of a factor of a 2–3 (Harries et al., 1998). However, asymmetry could be a significant factor for the small percentage of WR stars that become GRBs. A plausible distinguishing feature of the GRB WR stars is rapid rotation, so that the central core is rapidly rotating. For radiation driven winds, the higher gravitational acceleration on the polar axis can lead to a higher radiative flux and mass loss rate on this axis, although a lower temperature and higher opacity on the equator favors equatorial mass loss (e.g., Maeder, 2002); the density contrast from pole to equator can be a factor of a few. Meynet & Maeder (2007) have suggested that higher mass loss along the polar axis is needed so that the WR progenitor does not lose too much angular momentum through its wind.

Overall, the additional effects to consider for GRB progenitors compared to Galactic WR stars do not have a substantial effect on the expected wind density when compared to the large possible range of densities.

3 Circumstellar Interaction of Normal Type Ib/c Supernovae

The interaction of normal SNe Ib/c with their surroundings provides an interesting case of comparison for the GRB case because the driving force is generally understood for supernovae and there is synchrotron emission resulting from the interaction as in the the GRB case. In a normal supernova, the supernova shock wave accelerates through the steep density profile at the outer edge of the star; the acceleration stops when radiation can stream freely from the star. The radiation accelerates the outer gas and the radiation dominated shock front disappears. The shock wave re-forms as a viscous shock in the surrounding stellar wind. There is a shocked region bounded by a reverse shock on the inside and a forward shock on the outside. The reverse shock is in the steep outer power law portion of the supernova density profile. The shock fronts are plausible sites of particle acceleration; however, the material entering the reverse shock front has a very low magnetic field because of the supernova expansion, so there is some question of the efficiency of particle acceleration at that site.

The deceleration of the ejecta by the surrounding medium gives rise to a Rayleigh-Taylor instability and a turbulent region in the shocked layer. The magnetic field can be built up in this region, although it is not clear that the efficiency is high. In numerical simulations, Jun & Norman (1996) found that the field is strongest on the smallest scales. The energy density in the field was limited to $\sim 0.3\%$ of the turbulent energy density, but the result was limited by the numerical resolution. Another possible source of magnetic amplification is related to instabilities in the collisionless shock waves (e.g., Bell, 2004).

The basic hydrodynamic model of steep power law ejecta driving an interaction shell into a surrounding stellar wind can reproduce the observed radio emission from SNe Ib/c if some fraction of the postshock energy density goes into relativistic particles and magnetic fields, and synchrotron self-absorption (SSA) is important at early times (Chevalier, 1998; Chevalier & Fransson, 2006). In this situation, the peak flux of

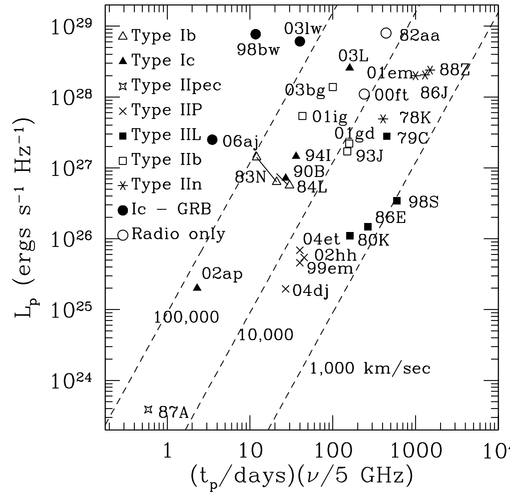

Fig. 1. Peak radio luminosity and corresponding age for well-observed core collapse supernovae. The dashed lines give curves of constant expansion velocity, assuming synchrotron self-absorption at early times (updated version of Fig. 4 in Chevalier (1998)).

the radio emission gives information on the radius, and thus the velocity, of the radio emitting region. Figure 1 shows observed peak fluxes and ages of radio supernovae. The dashed lines give the velocities of the radio emitting regions if the peak is due to SSA. If another absorption process, such as free-free absorption, is dominant, the velocity inferred from the turn-on is lower than the actual velocity. In Fig. 1, it can be seen that the SNe II have lower inferred velocities, which is both because of the relatively low velocities in SNe II and the importance of free-free absorption. There is a large range in peak luminosity for SNe II, which can be primarily attributed to a range in circumstellar density. Multiwavelength observations confirm the large range in density.

The normal SNe Ib/c show systematically higher velocities than the SNe II (Fig. 1), which can be attributed to some combination of higher peak velocities at the time of shock breakout, higher mean ejecta velocities because of lower ejecta mass, and lower deceleration because of lower circumstellar density. There is again a large range in peak luminosity; this may be due to a range in circumstellar density, but in this case there is no independent evidence for a range in density. If the supernovae have similar efficiencies for the production of synchrotron radiation and a range of circumstellar density that is comparable to that around Galactic WR stars, the observed luminosity range can approximately be reproduced if $\epsilon_B \approx \epsilon_e \approx 0.1$ (Chevalier & Fransson, 2006). The required magnetic field is high and cannot be produced by compression of the wind magnetic field (this would require a wind energy flux that was completely dominated by the magnetic field).

There are a number of X-ray observations of SNe Ib/c, but the data are much less extensive than at radio wavelengths (Chevalier & Fransson, 2006, and references therein). The observed luminosities are higher than expected from thermal emission from interaction with a normal WR star wind, so that a nonthermal mechanism is indicated. Near maximum light, inverse Compton scattering of photospheric photons with relativistic electrons is a possibility (Björnsson & Fransson, 2004; Chevalier & Fransson, 2006). At later times, inverse Compton emission fades because of the low supernova luminosity, and synchrotron emission is the most plausible nonthermal mechanism. However, an extrapolation of the radio synchrotron emission falls below the observed X-ray emission, especially when synchrotron cooling of the radiating electrons is taken into account. Chevalier & Fransson (2006) suggested a model of particle acceleration in a cosmic ray dominated shock front so that the particle spectrum flattens to high energy. At low energy, the particle spectrum is relatively steep, with energy index $p \approx 3$, in accord with radio observations of SNe Ib/c. At high energies, the spectrum becomes flat. This spectrum results in fairly flat evolution of the X-ray emission, while the radio emission decreases.

4 Low luminosity, nearby GRB-SNe

Figure 1 shows that the 3 low luminosity GRB/SN events have higher velocities of the radio emitting regions than the normal SNe Ib/c. Their positions in the figure suggest semi-relativistic velocities. The high luminosity nearby event GRB 030329 had a 5 GHz luminosity of 5×10^{30} erg s^{-1} Hz^{-1} on day 10 (Berger et al., 2003), indicating highly relativistic motion in this case. For the lower velocity cases, application of the synchrotron theory described by Chevalier & Fransson (2006) yields mass loss densities $A_*(\epsilon_B/0.1)$ of 0.1 (SN 1998bw), 1.6 (SN 2003lw), and 0.02 (SN 2006aj). The theory is nonrelativistic, but should still yield approximate results considering that these objects indicate only semi-relativistic motion. The density inferred for SN 2006aj is low because of the early turn-on (see also Waxman et al., 2007).

An important issue for the 3 low luminosity events is whether some of the observed phenomena can be explained by the supernova, or whether a central engine is needed, as in the case of normal GRBs. A supernova explanation means that emission associated with the interaction of the fast, outer supernova ejecta can explain the observations. Expectations for the supernova case depend on the ejecta mass and energy for the explosions. Optical observations of the 3 supernovae were extensive and there are results on the supernova parameters: 10 $M_\odot$ and 50×10^{51} ergs for SN 1998bw, 13 $M_\odot$ and 60×10^{51} ergs for SN 2003lw, and 2 $M_\odot$ and 2×10^{51} ergs for SN 2006aj (Mazzali et al., 2006a,b). The supernova properties of SN 2006aj were closer to the normal Ic SN 2002ap than to the bright SN 1998bw, and its inferred mass and energy would be incapable of producing the high velocity inferred from the radio emission. The implication is that the radio emission is related to a central engine. The radio observations of SN 2002ap suggest a low wind density in this case (Fig. 1), which appears to also apply to SN 2006aj. For SN 1998bw and SN 2003lw, the large supernova energy allows the possibility of a supernova origin for the radio emission. Tan et al. (2001) have discussed such a model for SN 1998bw.

SN 2006aj showed a thermal X-ray component over the first few 1000 sec that has been interpreted by Campana et al. (2006) and Waxman et al. (2007) as shock breakout emission. The temperature was constant at $\sim$ 0.17 keV during this time. The radiated energy in the thermal component was $\sim 2 \times 10^{49}$ ergs (Campana et al., 2006; Li, 2007). This is several orders of magnitude larger than would be expected from shock breakout from a WR star, assuming no effect of the WR star wind (Matzner & McKee, 1999); in addition, the duration of the shock breakout emission in this case would be determined by light travel time effects, yielding a timescale $\sim$ 10 s, much less than observed. Campana et al. (2006) addressed this issue by considering the progenitor star to be surrounded by a dense WR star wind, with $A_* \approx 20$. This wind density conflicts with that deduced from the radio emission, but the radio emission is at later times and it is possible that there was a phase of dense mass loss just before the explosion. With the dense wind, the photosphere is formed at $r \approx 5 \times 10^{12}$ cm. The corresponding light travel time, 200 sec, is still less than the duration of the thermal component, so Campana et al. (2006) and Waxman et al. (2007) appeal to an asymmetric progenitor structure to lengthen the timescale. Another issue is the total energy emitted in the thermal component, considering the fairly low energy explosion estimated for SN 2006aj mentioned above. Li (2007) considered supernova shock breakout in a wind and found that the energetics present a problem for SN 2006aj. However, Waxman et al. (2007) attributed the emission to the breakout of a mildly relativistic shell; it is possible that such shell ejection could be generated by a central engine. It thus appears that the early X-ray emission from SN 2006aj cannot be accounted for by the supernova and activity of the central engine is needed. Whether the thermal emission can be explained by breakout emission remains uncertain. One issue is whether the constant temperature emission can be produced if the progenitor is highly asymmetric. More detailed modeling of the emission is needed.

5 GRB Afterglows

As discussed in Section 2, the immediate surroundings of a long GRB is expected to be the wind from the progenitor star and one would expect the afterglow to reflect interaction with such a surroundings. In the time before a jet break occurs, there are clear differences between evolution in a wind medium and in a constant density (often referred to as ISM for interstellar medium) (Chevalier & Li, 2000). The cooling frequency, where the synchrotron cooling time equals the age, increases as $t^{1/2}$ in the wind case, but decreases as $t^{-1/2}$ in the ISM case. This frequency typically occurs between optical and X-ray wavelengths, giving the expectation that the flux should drop more rapidly with time at optical wavelenths than in X-rays for the wind case. The opposite is true for the ISM case. The peak flux, $F_{\nu m}$, at the typical frequency ν_m, is lower at lower frequencies $\propto \nu^{1/3}$ in the wind case, but is constant in the ISM case. This effect can be best observed at radio wavelengths because of the large range of wavelengths that they provide. Finally, the synchrotron self-absorption, ν_a, drops as $t^{-3/5}$ in the wind case, but is constant in the ISM case. Again, radio observations are generally needed.

The application of these differences to observed light curves is complicated by jet effects, which were generally found to occur at early times ($<$ 3 days) for bursts found during the *BeppoSAX* era. Models of the deceleration of jets have shown some features that are not present in the simple models (Granot, 2007), so there is uncertainty in the interpretation. Overall, detailed models of afterglows observed during the *BeppoSAX* era generally prefer interaction with a constant density medium, e.g., Panaitescu & Kumar (2002) who found that wind interaction was preferred for just 1 burst (GRB 970508) out of 10. However, Starling et al. (2007) recently were able to constrain the circumburst medium for 5 *BeppoSAX* sources, finding that 4 were consistent with a wind and 1 (GRB 970508) was consistent with ISM. One difference with the analysis of Panaitescu & Kumar (2002) is that radio data were not included. In the *Swift* era, there have been excellent data on early X-ray afterglows, but there have been few extensive multiwavelength data sets.

A reason for this is that the greater sensitivity of *Swift* compared to the previous GRB satellites, so the bursts are fainter in multiwavelength observations. In particular, there have been few radio light curves, although the radio emission can provide important constraints, as described above.

Another aspect of *Swift* bursts is that the jet break often appears fairly late in the evolution, if at all. To some extent, this can be attributed to the discovery of lower luminosity bursts. An advantage of such bursts is that there is the possibility of using the distinguishing properties of wind vs. ISM models discussed above. A well-observed burst is GRB 050820A, which did not show a jet break until an age $\gtrsim$17 days (Cenko et al., 2006). During the pre-jet break period, Cenko et al. (2006) found that the X-ray afterglow declines more rapidly than the optical afterglow, which is an indicator of ISM interaction. However, an ISM model that is consistent with the optical and X-ray properties overpredicts the radio emission. Cenko et al. (2006) expect a radio flux of 5 mJy on day 7, but observe a flux of 0.1 mJy. The low radio flux is consistent with a wind interaction model. Thus the situation is ambiguous.

In addition to the finding of late X-ray breaks in *Swift* bursts, optical observations sometimes show a break when none is present at X-ray wavelengths (e.g, Monfardini et al., 2006). This causes some uncertainty about the nature of the optical break and may indicate that the X-ray and optical emission come from different regions.

Although multiwavelength modeling provides the best constraints on afterglow models, the large set of X-ray light curves and spectra observed with *Swift* can be used for comparison with the expected "closure relations" for ISM and wind models. In a study of *Swift* bursts from the first 6 months of operation, Zhang et al. (2006) found that all the bursts were consistent with ISM interaction. However, when ν_c is below X-ray frequencies, the afterglow evolution does not depend on the density profile, limiting the number of objects for which an interesting result can be obtained. In a more recent study of 30 sources, Panaitescu (2007) found that 2/3 are consistent with ν_c below X-ray frequencies so the afterglow evolution does not depend on the density profile, 25% are consistent with ISM evolution, and 10% are consistent with wind evolution.

The afterglow modeling described above applies to the blast wave phase of evolution in which the ejecta have been decelerated by the surrounding medium. The development of rapid response optical/infrared telescopes has given the possibility of making observations before the blast wave phase has been established. The REM telescope may have observed GRB 060418 and GRB 060607A during the onset of the afterglow phase (Molinari et al., 2006). Before deceleration, the observed flux is expected to increase as t^3 (ISM) or $t^{1/3}$ (wind) (Molinari et al., 2006; Jin & Fan, 2007). The observed increases for the

2 bursts are consistent with a t^3 dependence and inconsistent with $t^{1/3}$, implying a constant density interaction. An estimate of the radius at which deceleration occurs is 10^{17} cm (Molinari et al., 2006), showing that the constant density medium must extend in to at least this radius. Another case where a sharp turn-on of the afterglow may have been detected is GRB 060206 (Stanek et al., 2007). If this interpretation of the rise phases is correct, the further light curves should be of the ISM type (or something more complex), and not of the wind type. The available information on these afterglows does not seem to fit the simple models. Another burst with early optical observations is GRB 050801, which Rykoff et al. (2006) found to have a flat flux evolution from $20 - 250$ s. The early flat evolution is roughly consistent with wind evolution, but the later afterglow evolution is consistent with ISM interaction, and not with wind interaction. It is possible that the burst made a transition from wind to constant density surrounding medium, but this would have to occur close to the deceleration radius. Although there are tantalizing clues from the early optical observations, they cannot be clearly interpreted in terms of the standard models.

One of the main findings during the *Swift* era is that X-ray afterglows are more complex than previously recognized, showing a variety of flaring behavior and an early plateau phase. Detailed observations of optical afterglows have also shown complex evolution (e.g., Dai et al., 2007). These observations point to later energy addition to the GRB blast wave than is assumed in the standard models. Our lack of knowledge of the expected form of the energy addition (unlike the supernova case) limits our ability to precisely deduce the nature of the surrounding medium. However, there is currently evidence for afterglow evolution in both wind and constant density media.

6 Short vs. Long GRBs

According to present thinking, the long GRBs are explosions in massive stars, while the short bursts result from the mergers of compact objects. These 2 progenitor types can be expected to have different environments: the long bursts occurring in the mass loss of the progenitor stars and the short bursts in the surrounding ISM. A comparison of the afterglows for the two types of bursts can then give an indication of whether the interpretation of long bursts interacting with a constant density medium is correct and is not the result of an effect such as the variation of microphysical parameters.

A good case is the analysis of GRB 051221A by Soderberg et al. (2006). The time of an apparent jet break was 5 days, so there was significant evolution in the pre-jet break regime. The X-ray afterglow decline was characterized by $\alpha = -1.06 \pm 0.04$, which, together with the X-ray spectral index, was consistent with evolution in the cooling regime. The flatter optical/X-ray spectral index and the flatter evolution at optical wavelengths were roughly consistent with evolution in a constant density medium with ν_c between optical and X-ray wavelengths, assuming a standard afterglow model. This result gives confidence in the application of the standard model to those long bursts with the deduction that they are expanding into a constant density medium. The similarity between the short and long burst afterglow evolution indicates that the apparent ISM interaction is not due to wind interaction with a particular evolution of the microphysical parameters.

The observations of the short bursts are generally consistent with interaction with a low density ISM. In the case of GRB 051221A, Soderberg et al. (2006) deduced a density $\sim 10^{-3}$ cm^{-3}. The lack of observable X-ray afterglows for some short bursts may be due to a very low surrounding density, $\lesssim 10^{-5}$ cm^{-3} (Nakar, 2007).

7 Producing a Constant Density Surrounding Medium

The evidence from afterglow modeling for constant density media around long GRBs has stimulated interest in producing such a medium around a massive star. The most plausible way of doing so is the medium produced downstream of the termination shock in the stellar wind (Wijers, 2001). This region has a roughly constant pressure because the sound speed is higher than the systematic velocities over most of the volume. In addition, the velocities are sufficiently high to make the flow steady over much of the volume, so that conservation of entropy with radius leads to a constant density region. The radius of the termination shock, R_t, can be estimated from the pressure generated at the shock

$$R_t = 5.7 \times 10^{19} \left(\frac{v_w}{10^3 \text{ km s}^{-1}}\right) \left(\frac{p/k}{10^4 \text{ cm}^{-3} \text{ K}}\right)^{-1/2} A_*^{1/2} \text{ cm}$$

where p is the pressure in the shocked wind and k is Boltzmann's constant.

A general problem is that the value of R_t needed to explain the afterglow observations is smaller than expected around a typical WR star. Afterglow models require that the termination shock be at a radius $\lesssim 2 \times 10^{17}$ cm in some cases (Chevalier et al., 2004). One factor is the reduced value of $\dot{M}$ because of the low metallicity of the progenitor (Wijers, 2001). As discussed in section 2, this reduces $\dot{M}$ by a factor ~ 3, which reduces R_t by up to ~ 2. Although this helps the problem, more is needed. The other possibility is increasing the pressure, which can be accomplished by interaction with a dense ambient medium, high ram pressure due to motion of the progenitor star, or high pressure of the ambient medium (van Marle et al., 2006; Chevalier et al., 2004). The finding of Fruchter et al. (2006) that GRBs occur in regions of strong star formation may be consistent with the presence of a high interstellar pressure, but this needs to be verified in more detail.

In the pre-burst models of van Marle et al. (2006), the wind from the WR star sweeps out the dense red supergiant wind from a previous evolutionary phase. However, there is increasing evidence for supernovae occurring soon after the loss of the the H envelope in dense mass loss; an example is SN 2001em (Chugai & Chevalier, 2006). GRBs might preferentially occur in such an explosion because there is less opportunity for loss of angular momentum in the WR wind. The dense mass loss then provides a wall for shocking the WR wind.

A possible problem for the shocked wind explanation of the constant density medium is the radial range over which it is required. Observations of some GRBs requires that the outer extent of the shocked wind be $\gtrsim 2R_t$, which rules out some wind interaction models (Chevalier et al., 2004). While some shocked wind models are consistent with these results, the lack of evidence for interaction with the region inside or outside the shocked WR wind is a possible problem. In particular, one would expect an interaction with a freely expanding wind followed by a transition to constant density medium. Early work on this transition indicated that there would be increase in emission when the shock was traversed (Wijers, 2001; Pe'er & Wijers, 2006), but Nakar & Granot (2006) find that there is no bump in the GRB light curve at this point. In any case, there should be a transition from the self-similar blast wave evolution in a wind medium to evolution in a constant density medium.

The evidence for the turn-on of some afterglows in an ISM medium (Section 5) is a problem for this model. The deceleration of the GRB ejecta in a wind occurs at a radius

$$R_{dec} \approx 4.0 \times 10^{15} E_{53} \Gamma_{0,2}^{-2} A_*^{-1} \quad \text{cm},$$

where E_{53} is the isotropic blast wave energy in units of 10^{53} ergs and $\Gamma_{0,2}^{-2}$ is the initial Lorentz factor of the GRB ejecta in units of 10^2 (Panaitescu & Kumar, 2000). The pressure needed to have the termination shock occur at or within this radius cannot plausibly be attained (van Marle et al., 2006), so a massive star progenitor may not be viable in these cases. A possibility is that some long bursts have compact binary progenitors and interact directly with the ISM. King et al. (2007) have suggested the merger of neutron stars and white dwarfs as possible long burst progenitors. These events would generally be associated with active star formation (but not always) and would not be accompanied by a supernova.

8 Clues from Absorption Lines

Possible information on the immediate surroundings of GRBs comes from absorption lines observed in the optical spectra. The mass loss processes leading up to explosion have the possibility of creating absorption features in the spectrum; in particular, the free wind is expected to have a velocity as high as 5000 km s^{-1}, which can be distinguished from typical velocities in the host galaxy. A redshift $z \gtrsim 2$ is needed so that the strong ultraviolet resonance line transitions are shifted into the optical. A case of special interest has been GRB 021004 ($z = 2.3$), which showed a number of absorption line systems with velocities up to 3000 km s^{-1} in observations by Schaefer et al. (2003) and Mirabal et al. (2003), who concluded that the features were likely to be circumstellar. Higher resolution observations have shown that the -3000 km s^{-1} line system can be separated into -2700 km s^{-1} and -2900 km s^{-1} systems (Fiore et al., 2005; Chen et al., 2007). The problem with the circumstellar hypothesis is that the radiation field of the GRB is expected to completely ionize the gas around the burst to a substantial radius (Lazzati et al., 2006; Chen et al., 2007). Mirabal et al. (2003) suggested that the high velocity features are due to clumps initially at some distance from the burst that are radiatively accelerated by the burst. However, it is not clear whether coherent acceleration by the radiation field could take place. An alternative point of view is that the 3000 km s^{-1} features are due to the freely expanding WR star wind, which has the advantage of naturally explaining the observed velocity. However, there is still the problem of the strong ionization. Lazzati et al. (2006) deal with this problem by suggesting that the WR wind termination shock is out at 100 pc, where the free wind is not completely ionized. This value of R_t is in the opposite direction to what is generally needed for GRB afterglows (Section 7) and requires an unusually *low* surrounding pressure, in addition to the low surrounding density assumed in the model of Lazzati et al. (2006).

Another problem with the WR star wind hypothesis is that the lines observed in spectrum of GRB 021004 include H lines, which are generally not expected in WR star wind at the end of the star's life. The presence of H would not be a problem if the absorption is formed in an intervening system. Chen et al. (2007) undertook a project to check whether absorption line systems in the velocity range $1000 - 5000$ km s^{-1} were due to intervening systems or to the progenitor winds. The finding of one high velocity system out of 5 observed GRBs was consistent with an intervening system. They also argued that the high velocity systems observed in GRB 021004 could be attributed to an intervening system, citing the presence of H I, C II, and Si II together with the absence of excited C II or Si II as evidence. Overall, it appears that absorption line observations are not likely to give information on the medium that the GRB is exploding into.

One way to demonstrate a relation between the absorbing gas and the GRB would be line variability due to the GRB radiation. The C IV absorption features in GRB 021004 were measured over 6 days but do not show any clear evidence for variability (Lazzati et al., 2006). Vreeswijk et al. (2006) found evidence for variability of Fe II and Ni II absorption lines toward GRB 060418. They showed that ultraviolet pumping of Fe II and Ni II excited- and metastable-level populations by the GRB radiation is plausible, but their model requires that the absorbing gas be $\gtrsim$1.7 kpc from the GRB. There is no significant Fe II or Ni II closer than this distance, presumably because of ionization by the GRB radiation.

9 Discussion and Conclusions

At the present time, there is a dichotomy between the supernovae and the GRBs. In the supernova case, the driving force for the interaction with surroundings is fairly well understood. The shock acceleration through the outer parts of a star does not depend on the details of the central explosion. Models for the nonrelativistic interaction with the surroundings of the progenitor star are straightforward and give strong support for models of interaction with a free wind. For GRBs, the relativistic, collimated flow depends on the details of matter and energy production by the central engine. Observations of afterglows in the *Swift* era have shown that the ejecta properties are probably crucial for understanding the early afterglow evolution.

The standard afterglow model is probably a better approximation at later times. From the beginning of afterglow observations, the standard interpretation of long burst afterglows have indicated that, in the majority of cases, the evolution is consistent with interaction with a constant density medium (except for Starling et al. (2007)). This trend has continued in the *Swift* era. The indications of a constant density medium include the evolution of the X-ray afterglow when the cooling frequency appears to be above X-ray wavelengths, and the evolution of the optical afterglow and its relation to the X-ray evolution. Radio observations do not support constant density interaction, and that is one of the main points against this picture. More recent support for constant density interaction in some cases comes from the sharp turn-on of optical afterglow emission. Also, the consistency of the standard constant density afterglow model with observations of short bursts gives confidence in the similar model when applied to long bursts; short bursts are expected to be interacting with a constant density ISM. In other cases, there is evidence for interaction with a wind medium.

There is thus sufficient evidence for constant density interaction that ways of producing such a medium must be considered. The inner boundary of the constant density medium must extend in to $\lesssim 2 \times 10^{17}$ cm. This is larger than the radial distance usually sampled by supernova observations, so there is not a clear discrepency between these cases. However, a constant density around a massive star is most plausibly produced by having the stellar wind pass through a termination shock, and the required radius is smaller than would typically be expected for a massive star wind at the end of its life. There is thus interest in how to produce a small termination shock radius for GRB progenitors.

One effect is the lower mass loss rate expected for the low metallicity progenitors of the GRBs, but additional effects are needed to bring in the radius. One possibility is that the GRBs occur in regions of the ISM with a high pressure, which reduces the value of R_t. Some support for this is that the bursts are observed to be more concentrated to star forming regions than are supernovae (Fruchter et al., 2006). The action of stellar winds and supernovae from massive stars can produce a high pressure. Other possibilities are a high space velocity in a dense medium or that the progenitor stars undergo a particular evolution that results in a small R_t. However, the observational evidence for interaction with a constant density medium at the GRB deceleration radius is difficult to reconcile with a shocked wind model and may indicate a compact binary progenitor in the ISM for these cases. In this situation, the GRB should not be accompanied by a supernova. The surroundings of GRBs may be indicative of various progenitor types.

Acknowledgements

I am grateful to Z.-Y. Li, C. Fransson and A. Soderberg for collaboration on these topics, and to NASA grant NNG06GJ33G for support.

References

Bell, A. R. 2004. MNRAS, 353, 550

Berger, E., et al. 2003. Nature, 426, 154

Björnsson, C.-I., & Fransson, C. 2004. ApJ, 605, 823

Campana, S., et al., 2006. Nature, 442, 1008

Cenko, S. B., et al., 2006. ApJ, 652, 490

Chen, H.-W., et al., 2007. ApJ, in press (astro-ph/0611079)

Chevalier, R. A. 1998. ApJ, 499, 810

Chevalier, R. A., & Fransson, C. 2006. ApJ, 651, 381

Chevalier, R. A., & Li, Z.-Y. 2000. ApJ, 536, 195

Chevalier, R. A., Li, Z.-Y., & Fransson, C. 2004. ApJ, 606, 369

Chugai, N. N., & Chevalier, R. A. 2006. ApJ, 641, 1051

Crowther, P. A. 2006, in Stellar Evolution at Low Metallicity: Mass Loss, Explosions, Cosmology, ASP Conf. Series, 353, 157

Dai, X., et al., 2007. ApJ, 658, 509

Fiore, F., et al. 2005. ApJ, 624, 853

Fruchter, A. S., et al. 2006. Nature, 441, 463

Fynbo, J. P. U., et al. 2006. Nature, 444, 1047

Granot, J. 2007, Revista Mexicana de Astronomia y Astrofisica Conference Series, 27, 140

Harries, T. J., Hillier, D. J., & Howarth, I. D. 1998. MNRAS, 296, 1072

Jin, Z.-P., & Fan, Y.-Z. 2007. MNRAS, in press (astro-ph/0701715)

Jun, B.-I., & Norman, M. L. 1996. ApJ, 465, 800

King, A., Olsson, E., & Davies, M. B. 2007. MNRAS, 374, L34

Lazzati, D., et al. 2006. MNRAS, 372,

1791
Li, L.-X., 2007. MNRAS, 375, 240
Maeder, A. 2002. A&A, 392, 575
Matzner, C. D., & McKee, C. F. 1999. ApJ, 510, 379
Mazzali, P. A., et al. 2006a. ApJ, 645, 1323
Mazzali, P. A., et al. 2006b. Nature, 442, 1018
Meynet, G., & Maeder, A. 2007. A&A, 464, L11
Mirabal, N., et al. 2003. ApJ, 595, 935
Modjaz, M., et al. 2007, ApJ, submitted (astro-ph/0701246)
Molinari, E., et al. 2006. A&A, submitted (astro-ph/0612607)
Monfardini, A., et al. 2006. ApJ, 648, 1125
Nakar, E. 2007. Phys. Rep., 442, 166
Nakar, E., & Granot, J. 2006, preprint (astro-ph/0606011)
Nugis, T., Crowther, P. A., & Willis, A. J. 1998. ApJ, 333, 956
Nugis, T., & Lamers, H. J. G. L. M. 2000. A&A, 360, 227
Panaitescu, A. 2007. MNRAS, submitted (arXiv:0705.1015)
Panaitescu, A., & Kumar, P. 2000. ApJ, 543, 66
Panaitescu, A., & Kumar, P. 2002. ApJ, 571, 779
Pe'er, A., & Wijers, R. A. M. J. 2006. ApJ, 643, 1036
Rykoff, E. S., et al. 2006. ApJ, 638, L5
Schaefer, B. E., et al. 2003. ApJ, 588, 387
Soderberg, A. M., et al. 2006. ApJ, 650, 261
Stanek, K. Z., et al. 2007. ApJ, 654, L21
Starling, R. L. C., et al. 2007, ApJ, submitted (arXiv:0704.3718)
Tan, J. C., Matzner, C. D., & McKee, C. F., 2001. ApJ, 551, 946
van Marle, A. J., et al. 2006. A&A, 460, 105
Vreeswijk, P. M., et al. 2006. A&A, submitted (astro-ph/0611690)
Waxman, E., Meszaros, P., & Campana, S. 2007, preprint (astro-ph/0702450)
Wijers, R. A. M. J., 2001. In Gamma-ray Bursts in the Afterglow Era, ed. E. Costa et al., 306
Woosley, S. E., & Bloom, J. S. 2006. ARA&A, 44, 507
Zhang, B., et al. 2006. ApJ, 642, 354