SLAC-PUB-12305
astro-ph/0701320
January 2007

Models for GRBs and diverse transients

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The observational diversity of "gamma-ray bursts" (GRBs) has been increasing, and the natural inclination is a proliferation of models. We explore the possibility that at least part of this diversity is a consequence of a single basic model for the central engine operating in a massive star of variable mass, differential rotation rate, and mass loss rate. Whatever that central engine may be - and here the collapsar is used as a reference point - it must be capable of generating both a narrowly collimated, highly relativistic jet to make the GRB, and a wide angle, sub-relativistic outflow responsible for exploding the star and making the supernova bright. To some extent, the two components may vary independently, so it is possible to produce a variety of jet energies and supernova luminosities. We explore, in particular, the production of low energy bursts and find a lower limit, $\sim 10^{48}$ erg s^{-1} to the power required for a jet to escape a massive star before that star either explodes or is accreted. Lower energy bursts and and "suffocated" bursts may be particularly prevalent when the metallicity is high, i.e., in the modern universe at low redshift.

Keywords: gamma-ray burst – models

1. Introduction

If the BATSE era was the age of discovery for GRBs, and the BeppoSax/HETE era, the age of cosmology (or at least when we clearly saw that bursts were at cosmological distances and associated with massive stars), then SWIFT may be remembered, in part, as the age of increasing diversity. GRBs now come in short and long varieties, as well as hybrids having properties of both long-soft and short hard bursts. There are long-soft cosmological x-ray transients, GRBs with supernovae, GRBs without supernovae, and energetic supernovae with weak GRBs. While it would be surprising if all cosmolgical transients lasting within 0.1 to 1000 s, with a power spectrum peaking between 1 keV and 1 MeV were the same thing, the parameter space for massive stars that die and produce a rapidly rotating compact remnant is really quite large, and diverse transients are to be expected.

2. A Two-Component Model

(a) *The Need for Two Components*

Any GRB that is accompanied by a stellar explosion with energy $\gtrsim 10^{51}$ erg must consist, inside the star that makes it, of at least two outflows - a highly relativistic core focused to a tiny fraction of the sky (typically a few tenths of a percent), and a broad angle, subrelativistic outflow (Fig. 1). The core jet, by itself, will not

Submitted to Phil.Trans.Roy.Soc.Lond.

Work supported in part by the US Department of Energy contract DE-AC02-76SF00515

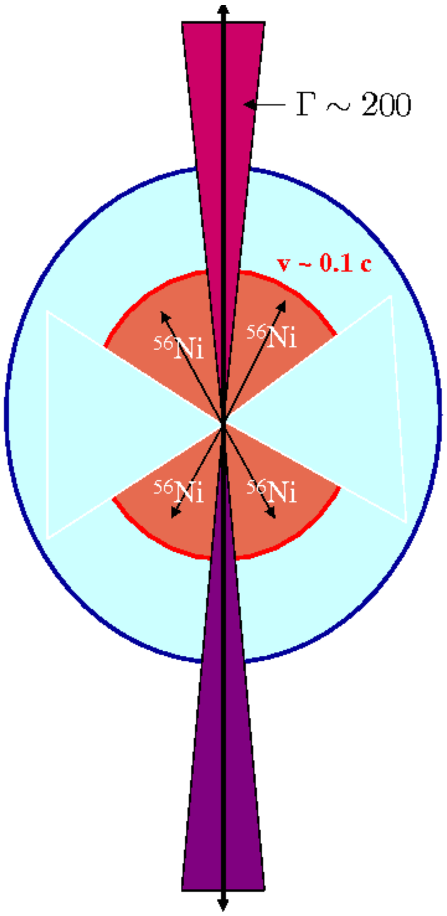

Figure 1. The jet in those GRBs which have accompanying supernovae must have at least two components - a narrow highly relativistic jet responsible for the burst itself and a broad subrelativistic outflow responsible for exploding the star and producing the ^{56}Ni to make it bright. The broad outflow extends to at least 1 radian. There may additionally be a mildly relativistic outflow (not shown) from the cocoon explosion that contributes to the afterglow and off-axis bursts.

violently explode the star (though the jet may be surrounded by a powerful cocoon), and no isotropic explosion with credible energy will give adequately relativistic ejecta to make a common GRB. In the millisecond magnetar model, the large-angle component could be an "ordinary" supernova, launched by neutrinos or MHD processes, and the narrow jet might be an afterthought, an MHD collimated outflow that happens after the supernova shock has already been launched. In the collapsar model, the jet is produced by MHD processes near the black hole, while the large angle outflow is from the disk wind (MacFadyen, 2003). It is the large angle outflow that is responsible both for most of the supernova's kinetic energy and the ^{56}Ni needed to make it bright.

(*b*) *Variable Supernova Brightness*

Because these two components have different origins, they are free, to some extent, to vary independently. In the collapsar model, whatever makes the jet involves physics very near the black hole. In the Blandford & Znajek (1977) model, for example, it is the rotation of the hole itself that powers the jet, the disk playing a passive role. In the neutrino version of the collapsar model (MacFadyen & Woosley, 1999), the jet is powered by neutrino annihilation along the rotational axis while the broad angle outflow comes from the "disk wind", energized by viscous processes farther out (MacFadyen & Woosley, 1999; Narayan et al., 2001). It is not difficult to envision situations where the relative importance of these two components varies. If the collapsing star has less angular momentum in its core, which is expected to be the case, for example, when the star has lost a lot of mass along the way, it will make a larger black hole before forming a disk. The accretion rate from the collapse of the lower density mantle farther out will also be less. It may be difficult in these conditions to realize a stable, neutrino-dominated accretion disk (Narayan et al., 2001). The accretion may be oscillatory (Woosley & Heger, 2006) and the composition of the wind - if there is one - is unknown. It may be some other nucleosynthetic product than ^{56}Ni

3. The Effects of Metallicity

The importance of metallicity in producing a GRB was pointed out by MacFadyen & Woosley (1999) and several observational studies have suggested a correlation of GRBs with low metallicity regions (e.g., Fruchter et al., 2006), though see Prochaska (2006).

In theory, metallicity and the final rotation rate of the stellar core are inversely correlated. This is because mass loss is dependent upon the iron abundance, especially during the critical Wolf-Rayet stage of the progenitor evolution that precedes the burst (Vink & de Koter, 2005; Woosley & Heger, 2006; Yoon & Langer, 2005, 2006). Mass loss saps angular momentum from the surface and the matter that expands to take the place of the lost matter rotates more slowly. This slower rotation is communicated by torques and circulatory currents to the layers deeper inside. Without an angular momentum, $j \sim 3 \times 10^{15}$ cm^2 s^{-1}, the rotational energy of a neutron star would be too low to power a GRB, let alone an energetic supernova like SN 1998bw. To form a disk around a 3 $M_\odot$ black hole in the collapsar model requires at least 2×10^{16} cm^2 s^{-1}. With less rotation, a supernova might still be possible, and even some sort of low energy transient, but for $j \lesssim 10^{15}$ cm^2 s^{-1}, some other means besides rotation must be found to blow up the star.

For those stars that do die with adequate angular momentum, the properties of the GRBs that they make should be correlated with the excess above these minimum values. Stars that lose less mass, on the average, die with more rapid rotation rates *and* greater mass. The latter characteristic makes them more tightly bound and gives greater accretion rates on the young collapsed core, making black hole formation more likely (Fryer, 1999). Both these properties favor the formation of a collapsar. Stars with the greater angular momentum form their disks earlier around less massive black holes. The temperature at the last stable orbit is then higher (Popham et al., 1999), which increases neutrino emission and allows the disk to dissipate its energy more efficiently. These neutrinos annihilate in a smaller volume making a neutrino-powered jet feasible. The total amount of mass available for accretion is also greater which makes for a longer more energetic burst. These properties make it more likely that the most energetic gamma-ray bursts will occur in regions with the lowest metallicity, though there can be considerable variation in individual events because of the mass of the star itself varies.

For higher metallicity, and hence less rotation, the black hole in the collapsar model forms later and accretes more slowly. The dynamical time scale for the matter that is left outside is longer, but there is also less of it. Neutrino emission becomes less effective, both as a power source for the burst and a means of dissipating disk binding energy. On the average, these bursts will last longer and have less total energy.

This all assumes a one-to-one relation between mass that falls to the center and mass that accretes, but even when a stable disk forms, that disk may experience considerable loss to a wind (MacFadyen & Woosley, 1999; Kohri et al., 2005). In fact, it is this wind, not the jet, that is responsible for blowing up the star. Either a low accretion rate (low rotation, high metallicity) or a very high angular momentum (high rotation, low metallicity) can reduce the neutrino losses and make black hole accretion less efficient. In the former case, the low accretion rate makes the temperature too low for effective neutrino dissipation. In the latter, the disk forms at such a large radius that neutrino dissipation is ineffective. If one associates the disk wind with the brightness of the supernova and black hole accretion with the strength of the GRB, then it is clear that considerable variation in the ratio can be expected.

For still lower rotation rates, making a GRB using black hole accretion becomes increasingly difficult and, if there is to be an energetic jet at all, one needs to consider neutron star models. In fact, the neutron star possibility is there all along, provided something (neutrinos?) can hold up the accreting star while the "proto-neutron star" experiences several seconds of Kelvin-Helmholtz evolution and shrinks to its final radius, rotation rate, and magnetic field strength (Thompson et al., 2004; Woosley & Bloom, 2006). To explain GRBs in the highest metallicity regions (i.e., solar), and lightest presupernova progenitors, it may be that this mechanism is necessary. On the other hand, neither the energy of a GRB nor its duration is a unique signature of a neutron star model, and there may be other paths to making a GRB in metal-rich regions that involve binary stars

4. Low Energy Bursts

(*a*) *A Minimum Power to Break Out*

Whether produced by a neutron star or by black hole accretion, the power of the jet in massive star models for GRBs is likely to vary significantly from source to source. In the collapsar model, the power is sensitive to the accretion rate, the stability of the accretion disk, the efficiency for turning accretion energy into directed relativistic outflows, and the rotation rate and mass of the black hole. In the millisecond magnetar model it is sensitive to the rotation rate and field of the neutron star and unknown efficiencies for producing collimated outflows. It is thus reasonable to inquire as the the outcome of jets of various powers released deep

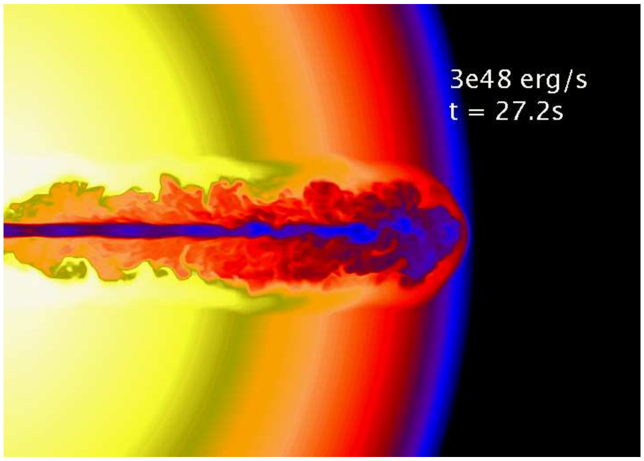

Figure 2. Three-dimensional calculation of a relativistic jet of 3×10^{48} erg s^{-1} introduced at 1×10^{10} in a 15 $\mathrm{M}_\odot$ Wolf-Rayet presupernova star of radius 8×10^{10} cm. The initial jet had Lorentz factor 5, total energy to mass ratio 40 and an initial cylindrical radius 1×10^{9} cm (~5 degrees). Plotted is the logarithm of the density as the jet nears the surface. The jet took much longer to reach the surface than a similar jet with power 3×10^{50} erg s^{-1} studied by Zhang et al. (2004) and was less stable. After break out, the jet eventually becomes more stable as an opening is cleared by the relativistic flow. For greater detail see Zhang & Woosley (2007).

within the progenitor star. How long does it take jets of varying energy to break out? Is there a minimum power below which jets do not make it out at all, or takes such a long time that the star would surely have collapsed or exploded in the meantime? This would imply an interesting limit on the power of bursts that can be produced directly by internal shocks within the jet. It is not a stringent lower bound, however, because the fraction of the jet energy in highly relativistic matter, and especially the efficiency for converting kinetic energy into gamma-rays is also uncertain and possibly highly variable.

Three jets of varying power, 0.03, 0.3, and 3×10^{50} erg s^{-1}, were introduced at 10^{10} cm in a 14 $\mathrm{M}_\odot$ Wolf-Rayet star of radius 8×10^{10} cm. The mass interior to 10^{10} cm was removed from the presupernova star and replaced by a point mass. Each jet is defined by its power, initial Lorentz factor (here $\Gamma = 5$), and the ratio of its total energy (excluding rest mass energy) to its kinetic energy (here 40). The parameters here are such that if the jet expanded freely to infinity, its Lorentz factor would be $\Gamma = 200$. The grid adopted in the 3D study Zhang et al. (2003, 2004) is Cartesian with 256 zones each along the x- and y-axes and 512 along the z-axis (jet axis). For full details of the calculations see Zhang & Woosley (2007).

Fig. 2 shows the density structure just as the 3×10^{48} erg s^{-1} jet erupts from the surface of the star 27 s after initiation at 10^{10} cm. The two other higher energy jets, 0.3 and 3×10^{50} erg s^{-1} took 15 s and 7 s respectively. It is also apparent in Fig. 2 that the structure of the jet itself is less coherent at low energy (compare with Zhang et al., 2004).

The long time for the jet to break out in Fig. 2 is comparable to the collapse time of the core, the sound crossing time for the core, and the duration of a common

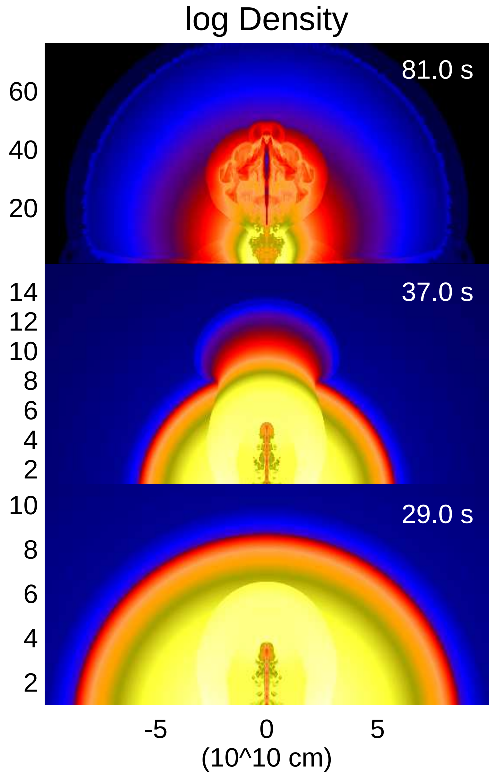

Figure 3. A still lower energy jet (1.0×10^{48} erg s^{-1}) is launched inside a star that is already in the process of exploding as a supernova (10^{51} erg deposited nearly isotropically within a cylindrical radius of 1.7×10^{10} cm near the origin at the bottom). The plot shows the density. The outer boundary of the supernova shock is visible at 29 and 37 s as the edge of the yellow-white oval. The jet power, 1×10^{48} erg s^{-1}, is so low that the it takes a very long time to break out. Still, if the power can be maintained for hundreds of seconds a bright transient could still be observed.At 81 s, the jet has expanded to 5 times the initial radius of the star and has overtaken the supernova shock.

GRB. An attempt to push a jet of only 10^{48} erg s^{-1} ended in failure. The jet had not emerged after 100 s. While a relativistic jet of arbitrarily low power will eventually break out of any star, the star in this case would either have largely accreted, reducing the energy of the jet further, or blown up. If it blew up, then the jet would have still further to go before breaking out.

If one assumes, as seems reasonable, that jets are unlikely to produce bursts much shorter than the time it takes them to escape their progenitor star, these calculations suggest that lower energy bursts will last longer. Ultra-relativistic jets with angle-integrated power much less than 10^{48} erg s^{-1} may be hard to make in massive stars. The energy the jet deposits in the star on the way out, essentially the break-out time times the power, also declines as the jet power is turned down. Thus, without the broad angle component (not included here), the supernovae accompanying weaker GRBs would also be weaker Zhang & Woosley (2007). Including the broad component can change this radically (§2).

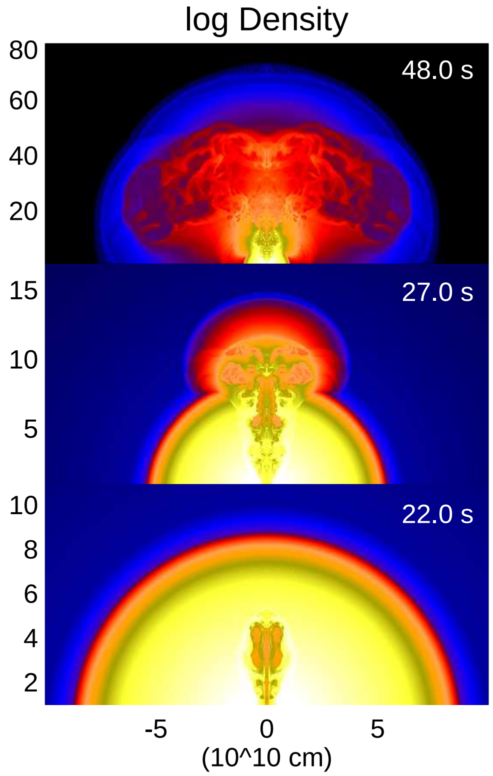

Figure 4. A jet of 3×10^{49} erg s^{-1} is turned off just before break out to simulate the cessation of accretion at the center of the star. The jet still caused a very asymmetric explosion and ejected mildly relativistic matter, but no hyper-relativistic jet core. There would be no GRB by internal shocks. However, there is mildly relativistic ejecta (Fig. 5), and the interaction of that matter with the presupernova wind would produce an energetic transient (Tan et al., 2001; Zhang & Woosley, 2007).

(*b*) *Decaying Jets*

A jet of lower lower takes longer to break out, but then the longer it takes, the more likely it is that the jet source has decreased further in power or the star has blown up already or both. Either case leads to a situation where a jet of declining energy finds itself still deeply embedded in dense, very optically thick matter.

Fig. 3 shows an event where a supernova with kinetic energy $\sim 10^{51}$ erg has already happened and its initial blast reached the surface of the star before a weak jet, in this case 10^{48} erg s^{-1}, finally arrives. The total energy in this jet, about 10^{50} erg per jet (and there is one at the other pole), is not especially small, just its power. A jet of any power will eventually break out, provided it is artificially maintained long enough, but unless it does there is no GRB. At both 37 and 81 s in Fig. 3 there is no material with Γ greater than about 2 except what is inside the jet, i.e., the supernova itself makes no strong hard transient. If the jet suddenly lost power at its base before 80 s, it would quickly share its energy with a large mass, and there would be no major relativistic event.

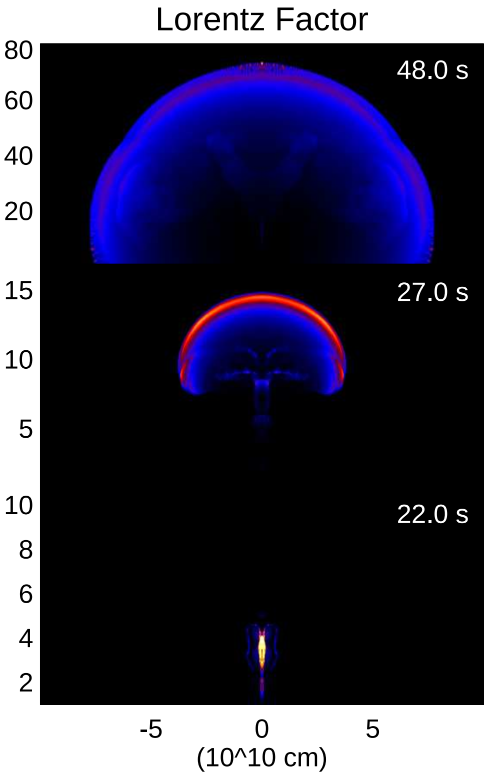

Figure 5. Lorentz factor corresponding to the models in Fig. 4. Red and purple correspond to Lorentz factors of about 3 and 2 respectively. At 27 s in this run, there are 1.5×10^{-8} $M_\odot$ and 1.2×10^{47} erg in material with a Lorentz factor greater than 2 and no material that has a Lorentz factor greater than 5.

This point is perhaps more clearly made in the model shown in Fig. 4 and 5. Here no supernova was assumed, but the jet, with power 3×10^{49} erg s^{-1}, was abruptly turned off at the origin at 22 s, just a few seconds before it would have erupted from the surface of the star. A highly asymmetric explosion still resulted, but the Lorentz factor of the jet, which would have been 200 had it coasted unimpeded to infinity, was quickly braked by running into the matter above. The blast spread sideways and by 48 s had become essentially isotropic so far as the relativistic matter was concerned. The total relativistic energy, Γ greater than 2, here was only 10^{47} erg, concentrated in about 10^{-8} $M_\odot$. For a mass loss rate of 10^{-5} $M_\odot$ y^{-1} before the explosion, this bit of matter would decelerate at a few $\times 10^{12}$ cm in a region which is optically thin. A transient lasting a few 10's of seconds, somewhat like GRB 980425 (Woosley et al., 1999; Tan et al., 2001), might result, although the total amount of relativistic matter in 980425 was probably at least two orders of magnitude greater.

However, the case shown in Fig. 4 is extreme. It is not natural that the central engine abruptly turns off at some point. The decline should be gradual. This would be the case for a steadily slowing pulsar at the origin, or for a black hole with a declining accretion rate. The results shown in Fig. 4 and 5 would then be augmented by additional energy and a higher Lorentz factor component that would be increasingly centrally concentrated at late times. A change of less than a factor of two in the total jet energy could affect the energy in relativistic matter by orders of magnitude, provided that just a little of that energy is provided to the jet after it has broken free.

(*c*) *Enshrouded Bursts*

Finally, any jet that is to produce a burst visible from far away must not only escape the star or supernova, but emerge intact from any optically thick wind near the star. The density in the wind, neglecting clumping and time variability, is about $\rho \sim 5 \times 10^{-13}\, \dot{M}_{-5}\, r_{12}^{-2}$ g cm^{-3}. The optical depth to electron scattering from radius $r_{12} \times 10^{12}$ cm is then $\tau \sim 0.1 \dot{M}_{-5}/r_{12}$. Here $\dot{M}_{-5}$ is the mass loss rate in 10^{-5} M$_\odot$ y^{-1}.

The relativistic jets in typical GRBs carry an equivalent isotropic energy that is at least the equivalent of the gamma-rays they ultimately produce. For reasonable radiative efficiencies, this implies a jet energy $\sim 10^{51}$ erg. With a Lorentz factor of 200, this is a rest mass of only $\sim$ a few $\times 10^{-6}$ M$_\odot$. Material moving at this speed would give up its energy if it encountered $1/\Gamma$ times its rest mass, or about 10^{-7} M$_\odot$. This is to be compared with the mass loss rate, which for typical bursts, especially in loss metallicity regions, is less than 10^{-5} M$_\odot$ y^{-1}, times the solid angle of the jet, say 1%. That is, the jet coasts to the distance the mass loss would go in one year, about 3×10^{15} cm before giving up all its energy. The GRB is produced well inside that radius and the afterglow near that radius and outside.

Consider, however, the circumstances for a jet with roughly 100 times less energy, i.e., 10^{49} erg, running into a wind with density ten times as great, i.e., 10^{-4} M$_\odot$ y^{-1}. Now, the jet encounters $1/\Gamma$ times its mass in the wind of only the last few hours. This corresponds to a radius of $\sim 10^{12}$ cm and a light crossing time of just a hundred seconds. The wind is optically thick at the radius where this interaction occurs. When such a ballistic jet enters this region, it will be braked and slowed, sharing its energy with a large mass. The explosion then becomes nearly isotropic, with mildly relativistic matter ejected at large radius (Fig. 4). One possibility is a long soft thermal x-ray transient (Campana et al., 2006).

5. Conclusions

GRBs are a rare branch of massive stellar death characterized by very rapid, highly differential rotation. GRBs will be easier to make, and may have more energy in stars with a lower iron abundance, for example, at higher redshift or in dwarf galaxies. It is important to note the key role played by iron here, not just total metallicity, i.e., oxygen. Iron and oxygen have different histories since the former is made mostly in Type Ia supernovae and the latter in Type II. Iron might be more deficient compared to solar than oxygen in some galaxies or regions of galaxies. Currently, models based upon complete mixing on the main sequence in very rapidly rotating single stars Woosley & Heger (2006); Yoon & Langer (2006) give an upper limit to the iron abundance allowed in a successful collapsar model of about 30% solar, but it is the rate at which angular momentum is lost in the Wolf-Rayet stage that matters, not the iron abundance itself. Less angular momentum will be lost per gram of mass lost if the winds are strongly concentrated at the rotational axis Maeder (2002). The estimates of magnetic torques from Spruit (2002) are highly uncertain. So too are the mass loss rates themselves, even for solar metallicity Wolf-Rayet stars. Therefore, single star progenitors of solar metallicity cannot be ruled out at this point solely upon the basis of theory.

A great variety of transients are possible depending upon the power and duration of the jet produced when the star dies, its Lorentz factor (and the time modulation, $\Gamma(t)$), the angle at which the event is observed, the mass loss rate, and the relative strength and composition of the broad angle component. Each of these, except the random viewing angle, may vary with the mass, metallicity, and rotation rate of the massive stellar population, and hence with red shift. On the average, one expects greater mass loss and hence slower rotation at higher metallicity so the GRBs in the modern universe may be qualitatively different from those long ago. In particular, they might have lower average energy and be more affected by a higher-density circumstellar environment.

GRBs are frequently, perhaps universally accompanied by bright Type Ic-BL supernovae (Woosley & Bloom, 2006). Indeed, it is difficult to imagine the production of a relativistic jet in a massive star by any means that does not require the star's death and at least partial disruption, and the evidence linking most long-soft GRBs to massive stars is strong. But the *brightness* of a supernova of Type I (the "super" in the "supernova") depends upon how much ^{56}Ni is made. In a collapsar it is possible that the dominant constituent of the disk wind is not radioactive. This happens if the density where the wind originates is unusually high, either because the viscosity is low or the wind dominantly comes from the inner disk (Pruet et al., 2003, 2004). In fact, material with electron mole number Y_e less than 0.482, will be free of ^{56}Ni. It is also possible that the wind in the collapsar model, or broad angle component in the neutron star model may, for some reason, be weak or fall back during the explosion. Much is still to be learned about these winds and limits on supernovae in nearby GRBs will be an important constraint. It is unfortunate that such information on bursts at higher redshifts - which might possibly be different beasts - is so difficult to obtain.

Finally, there is a minimum jet power, around 10^{48} erg s^{-1} that is capable of escaping a massive stars in a time comparable to the duration of most long-soft GRBs. On a longer time scale the star will either have exploded or accreted onto its compact remnant, either of which will affect the properties of the burst. If the star has already exploded (e.g., by neutrinos, the disk wind, or a large angle energy input by a pulsar), then the jet may have to play "catch-up" with the ejecta (Fig. 3). If the jet turns off any time in this period, a very weak transient will result. Similarly, if the central engine turns off before the jet breaks out (Fig. 4 and 5), no GRB results though the explosion is still quite anisotropic and some sort of x-ray transient may be observed. In what be the most natural case, a jet that does eventually break out but with greatly diminished power, what is seen will depend greatly on viewing angle and how long the jet stayed on after it broke out.

It is generally assumed that the interaction of the jet with the external medium will be negligible during the burst phase, at least in the internal shock model, yet dominant in the afterglow phase. For sufficiently high mass loss rates and GRB jets with sufficiently low energy will dissipate their energy close enough to the progenitor star to affect the burst. In some cases where a significant part of the jet energy has piled up in geometrically thin "plug" which the jet is pushing along, deceleration in a dense medium might give a short burst preceding a longer component from the usual internal shock interaction (Zhang et al., 2004). This might result in a "hybrid burst" with a brief intense initial spike from external shock interaction followed by a longer, more typical GRB (e.g., GRB 0600614 Gehrels et al., 2006). If the jet has less energy and dissipates within an optically thick region of the wind, its energy may spread out to larger angles in a way analogous to Fig. 4. One then might get a long x-ray flash visible at large angles. An example might be XRF 060218 (Campana et al., 2006).

Acknowledgments

This work has been supported by the NASA (NNG05GG08G) and by the SciDAC Program of the DOE (DE-FC02-06ER41438). Calculations were carried out on the Columbia computer at NASA-Ames. W.Z. has been supported by NASA through Chandra Postdoctoral Fellowship PF4-50036 awarded by the Chandra X-Ray Observatory Center.

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