10
Models for Gamma-ray Burst Progenitors and Central Engines

Stan E. Woosley
Department of Astronomy and Astrophysics,
University of California, Santa Cruz CA 95060

10.1 Introduction

For forty years theorists have struggled to understand gamma-ray bursts (GRBs), not only where they are and the systematics of their observed properties, but what they are and how they operate. These broad questions of origin are often referred to as the problem of the “central engine”. So far, this prime mover remains hidden from direct view, and will remain so until neutrino or gravitational-wave signatures are detected. As discussed elsewhere in this volume, there is compelling evidence that all GRBs require the processing of some small amount of matter into a very exotic state, probably not paralleled elsewhere in the modern Universe. This matter is characterized by an enormous ratio of thermal or magnetic energy to mass, and the large energy loading drives anisotropic, relativistic outflows. The burst itself is made far away from this central source, outside the star which would otherwise obscure it, by processes that are still being debated (Chapters 7, 8). The flow of energy is modulated by passing through the star, which also explodes as a supernova, and this modulation further obscures details of the central engine.

The study of GRBs experienced spectacular growth after 1997 when the first cosmological counterparts were localized (Chapter 4), and with that growth in data came increased diversity. Still it is customary to segregate GRBs into “long-soft” (LSBs) and “short-hard” (SHBs) categories (Kouveliotou 1993), though the distinction is not always clear (Chapters 3 and 5; Section [10.5.9]). Currently, it is thought that most SHBs result from the merger of compact objects - black holes and neutron stars - in galaxies and regions where the star formation rate is low. There are exceptions, such as GRB 050709, a short hard burst that happened in a star forming galaxy (Covino et al. 2006). But then Type Ia supernovae also happen in spiral
galaxies as well as ellipticals, and there is no reason to expect the SHB progenitor population to be exclusively confined to old galaxies (Prochaska et al. 2006), or even to galaxies for that matter. A few SHBs may be giant flares from soft gamma-ray repeaters in galaxies that are relatively nearby (Palmer et al. 2005; Tanvir et al. 2005). GRB 070201 seems to have happened in the Andromeda Galaxy (Mazets et al. 2008), but the event rate for compact mergers there is \( \sim 10^{-5} \cdot 10^{-4} \text{ y}^{-1} \) (Kalogera et al. 2004), and LIGO saw no signal (Abbott et al. 2006).

Most LSBs, on the other hand, are clearly associated with massive star formation and, since the lifetime of such stars is short, with massive star death. This connection is strengthened by the observation that many LSBs are accompanied by bright supernovae, when one might be detectable (Chapter 9; Woosley & Bloom 2006). Most LSBs must therefore be a consequence of neutron star or black hole birth, and that means that LSBs are some variety of core-collapse supernova. One of the greatest current challenges in the study of stellar evolution is separating out the physical conditions that lead to ordinary supernovae, which are much more frequent, and to LSBs. Are they a continuum, or is there something uniquely different about LSBs? It would help if we understood the mechanism of “ordinary” supernovae better. In fact, one of the greatest opportunities provided by LSBs is the possibility of an improved understanding of massive star death in general.

This chapter focuses on massive star models and is thus concerned chiefly, though not exclusively, with LSBs. This does not imply that massive stars are incapable of producing SHBs, only that the connection with LSBs is more clearly demonstrated. Indeed, the observational distinction between LSBs and SHBs is becoming blurred. For a recent review of SHBs see Nakar (2007), and Section 10.5.9.

10.2 Observational constraints

10.2.1 The long-soft burst host environment and progenitor masses

LSBs are not just extragalactic, they show a preference for high redshift. Prior to Swift, the mean redshift of LSBs was 1.3; now it is in the range of 2.2 (for 82 bursts, Jakobsson et al. 2006) to 2.6 (for 41 bursts with good redshift determinations, Fiore et al. 2007). Most bursts observed with Swift originate from a time when the Universe was only a few billion years old. This fixes LSBs to an epoch when galaxies and metallicity were both evolving rapidly and the star formation rate, at least in some galaxies, was high (Savaglio et al. 2008). Some bursts do come from relatively nearby galaxies,
but most of these are subenergetic (Kaneko et al. 2007). One possibility is that this reflects the evolution of metallicity in the Universe (Section 10.2.2 and Section 10.3.3).

LSBs are concentrated in small, irregular galaxies and are strongly correlated with the light in those galaxies, more so than Type II supernovae (Fruchter et al. 2006). In fact, the distribution of LSBs with light is similar to that of Type Ic supernovae (Kelly, Kirshner and Pahre 2008) and, to the extent that such supernovae are thought to originate from a very massive population, LSBs probably come from stars more massive than 20 $M_\odot$ on the main sequence (Larsson et al. 2007). Raskin et al. (2008), by constructing analytic models of star-forming galaxies and the evolution of stellar populations within them, find that the minimum progenitor mass on the main sequence for LSBs is likely to be above 40 $M_\odot$. Östlin et al. (2008) find that the progenitor of GRB 030329 was at least 25 $M_\odot$ with only a small probability of models as light as 12 $M_\odot$. Thöne et al. (2008) estimate that the progenitor of GRB 060505 had a mass of 32 $M_\odot$.

### 10.2.2 Metallicity

Since line-driven and grain-driven mass loss is metallicity dependent and mass loss removes angular momentum, one early prediction of the models (Section 10.3.3) was that LSBs should be easier to produce when the metallicity is low. Low metallicity has been observed for several local ($z < 0.25$) LSB sites (Sollerman et al. 2005; Stanek et al. 2006) as well as in distant LSB hosts (Fynbo et al. 2003; Christensen et al. 2004; Gorosabel et al. 2005; Fruchter et al. 2006; Prochaska et al. 2008). Savaglio et al. (2009), in a study of LSB host galaxies at an average redshift of $z = 0.96$, found evidence for subsolar metallicity in LSBs with an average metallicity of 1/6 solar for 17 of the hosts. Chen et al. (2008) found evidence for a declining ISM metallicity with decreasing galaxy luminosity in the star-forming galaxy population at $z = 2 - 4$, i.e., the appropriate range for LSBs. The average luminosity for 15 LSB hosts was about 10% that of a typical modern galaxy.

The broad-lined Type Ic supernovae that accompany LSBs have lower metallicity than those that do not accompany LSBs (Modjaz et al. 2008). This is particularly interesting, since the other broad-lined SN Ic’s at higher metallicity satisfy most of the other observational constraints – high mass progenitor, loss of hydrogen envelope, and asymmetry – required for GRBs.

Langer & Norman (2006) estimate that 10% of all stars ever born were born with metallicity less than 10% solar. The number and redshift distribution of low metallicity stars is then a credible match with what is seen
for LSBs. Campana et al. (2008) found evidence for (or at least consistency with) a progenitor with rapid rotation and low metallicity based on the X-ray spectrum of the surrounding material in GRB 060218. Specifically, the O/N and C/N ratios are difficult to explain without rotational mixing and low metallicity.

All in all, the data are consistent with LSBs exhibiting a preference for low metallicity regions, but still being possible, at least in a mild form, when the metallicity is not very much less than solar (see also Chapter 13).

10.2.3 Energetics and beaming

Making an LSB requires not just a lot of energy, but directed relativistic motion, i.e., a “jet”. The existence of jets was predicted by the models (Rhoads 1999), which required an asymmetric explosion to produce highly relativistic ejecta. This prediction was later confirmed by observations of achromatic breaks in the afterglow light curves (Fruchter et al. 1999; Kulkarni et al. 1999; Harrison et al. 1999; Stanek et al. 1999; Frail et al. 2001).

An important constraint on the central engine is the total energy of the burst and any accompanying supernova (Section 10.6.1). This energy includes both the non-relativistic ejecta, say $\beta \gamma \lesssim 2$, $v/c = \beta < 0.89$, and the relativistic ejecta. The non-relativistic ejecta include the supernova and, by far, most of the mass, but only the relativistic ejecta participate in making the LSB, and do so with less than 100% efficiency, perhaps much less. Energies inferred for those few supernovae that have been clearly seen with LSBs are typically a few times $10^{52}$ erg (e.g., Woosley & Bloom 2006), although aspherical explosions might work with somewhat less energy (Höflich et al. Wang 1999) for supernovae that have not been studied far out on the tails of their light curves. This requirement on the energy comes from the need to make a large mass of $^{56}\text{Ni}$, in order to make the supernova bright, and, simultaneously, to provide a high velocity to a large mass of ejecta. Gamma-ray bursts with equivalent isotropic energies up to $9 \times 10^{54}$ erg have been reported (Abdo et al. 2009), but the actual value is much less because of beaming. A better constraint on the total relativistic energy comes from analysis of the late time radio afterglow. Recent analysis of the most energetic Swift bursts (Chandra et al. 2008; Cenko et al. 2010a,b) suggests an upper bound that is, again, in excess of $10^{52}$ erg. It is not known whether these very energetic bursts also had comparably energetic supernovae, but if they did, the total energy may, in some cases, be a substantial fraction of $10^{53}$ erg.

The relativistic component can also be quite weak. Li & Chevalier (1999)
found only $\sim 10^{50}$ erg in the case of GRB 980425, and the matter may not have even been fully relativistic in the sense of $\gamma \beta > 2$ (Waxman & Loeb 1999). Given the large supernova energy in that event, the energy in relativistic ejecta was less than 1% that of the non-relativistic ejecta, though still much greater than for ordinary supernova. This contrasts with the $\sim 10^{51}$ found in the relativistic component of another supernova-related LSB, GRB 030329 (Kamble et al. 2009). There may also exist intermediate phenomena between supernovae and LSBs with very little, but non-trivial relativistic ejecta (Paragi et al. 2010).

10.3 Constraints from the models

10.3.1 Wolf-Rayet stars

Another early prediction of the models (Woosley 1993) was that LSBs would only be produced by massive stars that had lost their hydrogen envelopes, i.e., Wolf-Rayet stars of some sort. There are two reasons the envelope must be lost. First, a relativistic jet produced by any mechanism will not escape a hydrogenic star during the characteristic duration of an LSB (Woosley et al. 2004). The radius of even the most compact progenitors of supernovae with hydrogen in their spectra (Type II) is about 100 light seconds, and the head of the jet travels inside the star substantially slower than light. It might be possible to have a kind of very long transient if the central engine operated for several minutes, but then it seems unlikely that a jet would break out after such a long time and produce a burst that only lasted a few seconds. Probably such a jet, if one were ever made in a blue or red supergiant, would die in the envelope producing an asymmetric supernova and an X-ray transient (MacFadyen et al. 2001).

A second problem with any sort of giant progenitor is that it implies a slowly rotating helium core. If an envelope is present, the helium core must have spun at a high rate for a very long time while embedded in a medium that was essentially stationary. For current estimates of magnetic torques (Spruit 2002), the rotation of the iron core when the star dies would be too slow to make an LSB (Heger et al. 2005). An obvious implication is that any supernova seen in conjunction with an LSB must be Type I, not Type II. This is consistent with observations so far.

10.3.2 Rotation

The existence of jets and the inability, so far, of isotropic models powered by neutrino deposition to make very energetic supernova explosions strongly
suggest that the power source for most LSBs is rotation. That rotational energy, which ultimately is derived from the gravitational contraction of the core, could take several forms - the orbital motion of a disk or the rotational kinetic energy of a neutron star or black hole - but it is the energy extracted from rotation that powers the jet. While spherically symmetric shock breakout (Colgate 1968; Chevalier & Fransson 2008) can produce soft X-ray transients in WR-stars that might be powered by neutrinos in a non-rotating model, the power and hardness of an LSB spectrum requires much more energy per solid angle (Tan et al. 2001).

That being the case, the preservation of angular momentum is crucial. Since the LSB production rate is at least two orders of magnitude less than the supernova rate, even of Type Ib/c (Bissaldi et al. 2007), and since the required rotation rate exceeds that of even the fastest solitary pulsars by an order of magnitude, rotation is probably the governing factor that determines whether a massive star death will produce an LSB. Efforts to produce rapidly rotating systems fall into three categories: interacting binaries, single star models with low magnetic torques, and models based on the near homogeneous evolution of massive stars with exceptionally high rotation rates on the main sequence.

Most binary merger and “spin up” models ignore magnetic torques in the late stages of stellar evolution (e.g., Ivanova et al. 2002; Joss & Becker 2007)). They thus offer no obvious advantage over single star models that also ignore magnetic torques (Heger et al. 2000; Hirschi et al. 2005) and easily produce copious LSB progenitors. Indeed, two major problems facing all models that ignore magnetic torques are the overproduction of LSBs and the lack of any clear alternative for making the observed slow rotation rates of ordinary pulsars. Binary models also usually overlook the large degree of differential rotation that develops in LSB progenitors during their late stages of evolution. Studies by Petrovic et al. (2005, 2006) show that when magnetic torques are included, mass transfer prior to helium ignition offers no clear advantage over single star evolution. Maintaining the surface rotation rate of a Wolf-Rayet star (i.e., after the progenitor had lost its hydrogen envelope) at a significant fraction of Keplerian throughout helium burning would help mitigate the loss of angular momentum by mass loss, and would therefore be beneficial. This might be helpful in making some rotationally powered supernovae, or even low energy LSBs at solar metallicity (Section 10.2.2), but even this would require the accretion of helium or tidal locking in a very close binary.

What is often overlooked in binary models for LSBs, especially those that invoke tidal locking, is that the deep core must have sufficient angular
momentum to form a disk or a millisecond pulsar, not just the surface of the star. The oxygen shell that bounds the part of the core that collapses to a neutron star or black hole has a typical radius of 2000 to 3000 km. If this shell rotated with a period of 3 hours as in a rigidly rotating star in a very close, tidally locked binary, the specific angular momentum at that shell would be $j \sim 5 \times 10^{13} \text{ cm}^2 \text{s}^{-1}$, far too slow to power either a collapsar or a millisecond magnetar. If the disk did not form from material inside the carbon-oxygen core, which has a radius only about ten times bigger ($j \sim 5 \times 10^{15} \text{ cm}^2 \text{s}^{-1}$, but $M \sim 10 M_\odot$), it is hard to see how the burst could be accompanied by a supernova with the kind of spectrum and light curve that have been observed in nearby events. Still such models (Tutukov & Cherepashchuk 2003; Firmani et al. 2004; Van den Heuvel & Yoon 2007) are interesting for giving sufficient angular momentum in the outer solar mass or so to form a disk. Black hole formation in such systems would result in a collapsar of a sort and may be common occurrences. While this makes them well worth exploring, the characteristic time scale for such events would be much longer than for typical LSBs (Section 10.5).

The second alternative is to admit the existence of magnetic torques, but to question the accuracy of the Spruit (2002) formulation. Certainly it is difficult to know the strength of the magnetic field generated by the dynamo action of instabilities in the radiative layers of a massive star with any accuracy. It is agreed that any purely poloidal field should suffer from instabilities on the magnetic axis of the star (Tayler 1973), but what is the amplitude of these instabilities and can they drive a dynamo? Even more problematic is the dissipation rate one assigns to these fields, once generated. Not surprisingly, there are diverse views on the answer. Braithwaite has carried 3D MHD calculations of the Spruit-Tayler instability and finds results (Braithwaite 2006, 2008) essentially consistent with Spruit. Denissenkov & Pinsoneault (2007) on the other hand find a greatly reduced magnetic viscosity, but their formulae give a sun with a rapidly rotating core contrary to observations and have been criticized (Spruit 2006). Zahn, Brun and Mathis (2007) see the instability, but do not see a sustained dynamo action that could regenerate the mean fields. Yoon et al. (2008) studied magnetic field creation in a convective dynamo and found it not too much smaller in the radiative regions outside the convective shells than the Spruit fields. Suijs et al. (2008) took a more empirical approach, examining the rotational velocity of white dwarfs generated in stellar evolution calculations that include or do not include torques at the level computed by Spruit. Only when the torques are included do they get rotation rates slower than the observed upper bounds. Ignoring torques gives rotational rates two orders of mag-
itude bigger and inconsistent with observed upper bounds, but there may be other ways for white dwarfs to shed angular momentum (Charbonnel & Talon 2005). Clearly the last word has not been written here.

Assuming the approximate accuracy of the torques calculated by Spruit, Heger et al. (2005) find rotation rates for neutron stars at birth that are within a factor of two of what is observed for the youngest, most rapidly rotating pulsars (a still slower result from the models would be preferable). They also find angular momenta for the presupernova core of common supernovae that are too small to power LSBs by either the collapsar model or the magnetar model (Section [10.3]), but perhaps large enough, in the more massive stars, to make magnetars and rotationally powered supernovae. Again, a key point is that the star must lose its hydrogen envelope before burning much of its helium. However, one then becomes subject to the rapid mass loss rates of WR-stars. An important recent development is the realization that WR-star mass loss rates are very sensitive to metallicity (Section [10.3.3]). Another possibility is that WR mass loss occurs preferentially along the rotational axis and therefore extracts less angular momentum from the star (Meynet & Maeder 2007; Georgy et al. 2008). It is probable that some combination of removal of the envelope in a binary system, asymmetric mass loss in the WR stage, and perhaps minor adjustment of the parameters in the magnetic torque model can give stellar progenitors, at death, with sufficient angular momentum to make an LSB by the magnetar model, even at solar metallicity. A moderate decrease in metallicity may even allow the existence of collapsars.

The third possibility is that the candidate stars are very rapidly rotating from birth and that this dramatically changes their evolution, even on the main sequence. The necessary rotational speeds are over 300 km s$^{-1}$ and possibly 400 km s$^{-1}$ at the equator, depending on metallicity. Such values are on the high-velocity tail of what is observed. Stellar evolution studies show that such stars, due to the operation of strong Eddington-Sweet circulation, have a novel sort of “quasi-chemically-homogeneous” evolution (QCHE; Maeder 1987; Langer 1992; Yoon & Langer 2005; Woosley & Heger 2006; Yoon et al. 2006). They burn almost all their hydrogen to helium on the main sequence and never expand to become giant stars, going instead straight to the WR branch from the main sequence. QCHE has been invoked to understand nitrogen-rich and helium-rich massive main sequence stars in the Magellanic Clouds (see refs in Yoon et al. 2006). A combination of models is also possible in which accretion from a binary companion spins up a star to the point where it experiences QCHE (Cantiello et al. 2007). Because the large density contrast between helium core and envelope never
develops in stars that experience QCHE, the core is not spun down nearly so much during helium burning. Even with the inclusion of standard Spruit magnetic torques, the iron cores of such stars rotate very rapidly. The two groups who work on this sort of model (Woosley & Heger 2006; Yoon et al. 2006) find that a moderate decrease in metallicity (to reduce WR mass loss) results in LSB progenitors with sufficient angular momentum to make a collapsar. Yoon et al. concluded that LSB production would occur for metallicities $Z < 0.004$ so that 50% of all LSBs would happen beyond redshift $z \approx 4$. That estimate is probably overly restrictive. LSBs might be made by magnetars, which require less angular momentum than collapsars, and the distribution of iron in low mass galaxies with redshift may be different than that of oxygen in high mass galaxies. The observability of distant bursts in a flux-limited sample could also complicate matters.

A final possibility that could account for a small fraction of LSBs is that the progenitor does not directly involve the death of a massive star. An example could be black holes merging with white dwarfs (Fryer et al. 1999). There the amount of angular momentum is so large that an unusual kind of burst is predicted, probably a very long one.

### 10.3.3 Metallicity

Even on the main sequence, stars of lower metallicity are found to rotate more rapidly (Maeder & Meynet 2001; Ekström et al. 2008). Observations suggest that differences in rotation rate persist all the way to the zero age main sequence (Martayan et al. 2007), suggesting that low metallicity stars may also be born rotating faster, but see also (Peng et al. 2005). Reducing the mass loss also results in a star that, at death, is heavier and thus more prone to making a black hole, a requisite for the collapsar model. Extremely low metallicity may also alter the initial mass function, producing heavier stars that would frequently make black holes (e.g., Yoshida et al. 2006).

It is important to note the key role of the element iron here. Mass loss in red giant stars is dependent on dust grain formation, which will also be suppressed at low metallicity, but mass loss during the red giant stage is not so relevant here. Unless the complete envelope is removed quickly, any reasonable residual envelope will brake the rotation of the core. It is the large number of iron lines that provide the opacity for WR-star winds. The initial carbon and oxygen abundances, and even the larger abundances of these elements made by the star itself do not matter, unless the iron abundance is so low that mass loss would be negligible (Vink & de Koter 2005). Frequently, astronomers measure other elements from which they
derive “metallicity”, but the nucleosynthetic history of iron is different from that of oxygen and at low metallicity, the iron to oxygen ratio might be as much as four times less than solar (Nissen et al. 2002). Of course, it should go without saying that the iron abundance that matters is the one for the star that blows up, not some other part of the galaxy that it died in.

One does not expect the metallicity cutoff to be a sharp one, but as the metallicity increases, the collapsing cores of massive stars will tend to have less mass and angular momentum. All else being equal, this would imply that the bursts seen closer by, presumably with higher average metallicity, would be less energetic, as seems to be the case. Of course, it is easier to discover weaker bursts that are nearby, but analysis of Swift data by Kocevski & Butler (2008) suggest that nearby bursts are less energetic.

In the collapsar model, one would also expect that decreasing metallicity would increase the reservoir of material available to form a disk and thus increase both the duration and total energy of the jet. So far searches for such a correlation have been inconclusive, and suggest that the duration may actually decrease with red shift (Wei & Gao 2003; though see Section [10.5.9]).

### 10.3.4 Mass

If LSBs accompany neutron star or black hole birth, they must come from stars with main sequence masses of at least 8 $M_\odot$. Since the helium and heavy element shells of presupernova stars in the 8–12 $M_\odot$ range have little mass, it would be difficult to produce more than a trace of $^{56}$Ni in any explosion, so any supernova would be faint. Such light stars also do not lose their envelopes unless they are in a close binary and they have long evolutionary times during which magnetic torques could slow their rotation. It seems a safe bet that LSBs come from stars considerably more massive than 10 $M_\odot$, a fact consistent with observational limits (Section [10.2.1]).

Much beyond that though, theory offers uncertain guidance. In the QCHE models (Section [10.3.2]), rotationally-induced mixing leads to progenitors almost entirely composed of oxygen that are not much smaller than the star’s mass on the main sequence, especially if the metallicity is low. A 16 $M_\odot$ main sequence star with very rapid rotation might lead to a 14 $M_\odot$ presupernova model capable of making a collapsar (Woosley & Heger 2006). Without QCHE, a 14 $M_\odot$ helium core would have required a 35 $M_\odot$ main sequence star (Woosley & Weaver 1995), so the mixing has a big effect.

The gravitational binding energy of a presupernova star increases rapidly with the mass of the helium core and for masses over $\sim 8$ $M_\odot$ (i.e., the helium core of a 25 $M_\odot$ star evolved without rotation) exceeds $10^{51}$ erg (Woosley
et al. 2002). This makes it harder for the star to explode, and makes it more likely that some matter will fall back in those that do explode. Shallower density gradients near the iron core also result in a larger accretion rate on the proto-neutron star during the first few seconds of the explosion, increasing the likelihood of a “failed” explosion in which a black hole forms. Fryer (1999) estimated that black holes would form during the deaths of non-rotating main sequence stars heavier than 20 M⊙ from fall back, and would form promptly for stars above 40 M⊙. Several caveats are in order though. First, as mentioned, rotation substantially alters the relation between helium core mass and main sequence mass. Fryer’s 40 M⊙ limit could correspond to a rapidly rotating main sequence star of only 20 M⊙. Second, his calculations assumed the physics and (two-dimensional) codes of 1995. Many calculations since have given diverse results, and the definitive studies in three dimensions have yet to be done, even without rotation. Finally, it may not be necessary to make a black hole to generate a LSB. The magnetar model obviously does not require this. However, in the magnetar model, LSBs with bright supernova still require a massive progenitor to make adequate 56Ni (Nomoto et al. 2005, 2007).

Theory also suggests that too big a mass could actually impede the production of an LSB (Yoon et al. 2006; Woosley & Heger 2006). This is because more massive WR stars are currently thought to lose mass at a greatly accelerated rate that more than compensates for their reduced lifetime. The maximum value depends upon what is assumed about metallicity and uncertain mass loss rates, but the limit is larger at lower metallicity. In very massive stars that produce presupernova helium cores over 45 M⊙, the pulsational pair instability is encountered (Section 10.5.8). For QCHE and no mass loss, the limit could be as low as 45 M⊙ on the main sequence.

Taken together, the observational limits on mass are consistent with those from theory, but it would not be surprising to find an LSB coming from a star with a main sequence mass of 15 M⊙, or even less if the rotation rate were high and the metallicity (i.e., WR mass loss rate) very low (Yoon et al. 2006).

10.4 Central engines – A tale of two models

The association of LSBs with massive star death has rekindled an age-old debate regarding the mechanism by which supernovae explode. Since the 1930’s it has been realized that supernovae are a consequence of gravitational collapse in the cores of highly evolved massive stars (Baade & Zwicky 1934; Oppenheimer & Volkov 1939), but there are three ways this might come
The iron core may collapse to a neutron star that is slowly rotating and make an explosion powered by neutrinos (Colgate & White 1966), or it may make a rapidly rotating neutron star whose rotation powers the explosion by magnetic processes (Ostriker & Gunn 1971). More recently it has been realized that black hole formation can also power energetic explosions if the star has sufficient rotation to form a disk around the hole (Woosley 1993).

The necessary angular momentum in the rotational models is much larger than is observed in common pulsars, suggesting that either pulsars are somehow braked during (though see Ott et al. 2006) or after (though see Heger et al. 2005) their birth, or that only a small fraction of supernovae are powered this way. Recent multi-dimensional simulations that ignore rotation have been successful in blowing up at least the lightest supernovae with just neutrinos (Janka et al. 2007; Burrows et al. 2007a; Messer et al. 2008), and it is a reasonable expectation that 15 to 20 M⊙ progenitors might also explode if the calculation is done carefully in three dimensions. This would be enough to explain the majority of ordinary supernovae and would be consistent with pre-supernova model calculations (Section 10.3.2) that give slowly rotating cores for pre-supernova stars in this mass range. Since LSBs are rare, they are not constrained by pulsar statistics and may come from unusual stellar evolution. Moreover, the rapidly rotating compact object may either be a black hole or have such a strong magnetic field that any remaining pulsar is rapidly braked.

10.4.1 The millisecond magnetar model

A neutron star born with a rotation rate of \( \sim 1 \) ms (the maximum rate without large scale deformation and rapid braking by gravitational radiation) contains a large amount of energy, \( E = \frac{0.5I\Omega^2}{3 \times 10^{52}} \) erg for a moment of inertia \( I = 80 \text{ km}^2\text{M}_\odot \) (Lattimer & Prakash 2007). The dipole spin down luminosity, \( L \sim B^2R^6\Omega^4/c^3 \sim 10^{50} \text{ erg s}^{-1} \) for \( B \sim 10^{15} \) Gauss, is typical of LSBs and the supernovae that accompany them. Magnetars (Thompson & Duncan 2006) are known to have a magnetic field strength close to what is needed (Woods 2008). They are found in young supernova remnants and are observed to be spinning down rapidly. They may be surrounded by disks from fallback debris in the explosion (Wang et al. 2006), but are not powered by these disks. Their birth rate in our Galaxy is estimated to be 0.1 per century (Kouveliotou et al. 1998) or more (Gill & Heyl 2007; Muno et al. 2008), and they seem to be derived from a stellar population that may be heavier than 30 M⊙ (Muno et al. 2006; Muno
Models for Gamma-ray Burst Progenitors and Central Engines

2008), though see Davies et al. (2009). Given that their birth rate is not too much smaller than that of ordinary supernovae, only a small fraction (≈ 1%) of all magnetars can make bright LSBs when they are born. The birth of the rest could contribute to supernova energetics and asymmetry much more frequently, however, and only a subset with particularly high magnetic field and rotation rate in stars without hydrogen envelopes might make LSBs. It is interesting in this regard that stellar evolution calculations predict that neutron stars with more rapid rotation rates are made in more massive stars (Heger et al. 2005) and that the distribution of LSBs in their host galaxies suggests a correlation with very massive stars (Wachter et al. 2008; Section 10.2.1).

Recent models of millisecond magnetars show that they are capable of producing relativistic outflows (Bucciantini et al. 2008; Komissarov & Barkov 2008) and might be the source of LSBs (Usov 1992; Duncan & Thompson 1992; Thompson et al. 2004). A compelling case can be made that magnetar activity may be involved in producing a significant fraction of supernovae as well. So long as rapid rotation (P < 5 ms) is required to create magnetar-like magnetic fields (Duncan & Thompson 1992, 1996), a rotational energy ≳10^{51} erg must be dissipated by the neutron star. If that energy does not come out as neutrinos or gravitational radiation, then it must be an appreciable contribution to the supernova’s kinetic energy. There are two ways out of this. The iron core may not rotate this fast when it collapses and contracts to R ≈ 10 km. This is apparently the case for the roughly 90% of supernovae that do not make magnetars, but make ordinary pulsars instead. Alternatively, the energy of the rotation might be thermally dissipated into neutrinos. Calculations so far (Dessart et al. 2008) do not show this happening.

Despite these favorable arguments, it has not yet been demonstrated that a magnetar model can produce an LSB. In some calculations, the rotational energy is dissipated in sub-relativistic outflow (i.e., the supernova) leaving little to power the burst (Dessart et al. 2008). In others a prior supernova (Bucciantini et al. 2008) or initial conditions that readily make a supernova (Komissarov & Barkov 2008) are assumed in order to relieve the accretion onto the pulsar. This is not surprising. A fully MHD 3D simulation of core collapse including realistic neutrino transport and high density physics will be hard. But it will be necessary because neutrinos alone seem unlikely to launch a successful shock in the same very massive stars where they have failed for so long. The model must also satisfy some rather tight constraints on energetics and nucleosynthesis (Section 10.6.2).

If magnetars make LSBs, then their jets are likely to be Poynting flux
dominated. Neutrino energy deposition would not make a jet as in early versions of the collapsar model (MacFadyen & Woosley 1999), and the current models suggest magnetically dominated jets (Bucciantini et al. 2008, 2009).

10.4.2 The collapsar model

Supernovae must occasionally, and perhaps frequently, leave black hole remnants. We see black holes, or their effects, in binary systems and apparently some of them rotate very rapidly (McClintock et al. 2006; 2007; Liu et al. 2008). In some cases, these black holes are quite massive (Orosz et al. 2007), suggesting the collapse of the entire helium core. It is believed that the rapid spin and large masses reflect natal properties, not the effects of accretion in a binary.

A black hole can be formed in a supernova either promptly or by fall back. If it is by fall back, then the loosely bound hydrogen envelope may be ejected in the process. If not, in the absence of rotation, the entire star must collapse. For decades, calculations of iron-core collapse in non-rotating massive stars over about 25 $M_\odot$ formed black holes promptly (Fryer 1999; Buras et al. 2006), though the defining 3D studies have yet to be done. It is thus a reasonable, if unproven, assumption that some massive stars form black holes without initially developing violent explosions in their cores. That being the case, a black hole and an accretion disk must ultimately come to exist, since the outer layers, even of red supergiants, have too much angular momentum to fall into the hole directly. Several studies now show that black holes experiencing very rapid, optically thick accretion will produce relativistic outflows (Komissarov 2001; McKinney & Gammie 2004; Hawley & Krolik 2006, Barkov & Komissarov 2008; Tchekhovskoy et al. 2008). It is thus reasonable to expect that some kind of luminous transient will accompany the prompt birth of a black hole. The transients need not all be ordinary gamma-ray bursts however. The free fall time of red supergiant envelopes is hours to days. The observable signal might more closely resemble an ultra-luminous X-ray source (Li 2003) or even a blazar (Section 10.5).

If the inner core rotates more rapidly though, and a black hole is formed promptly, an LSB can result (Woosley 1993; Woosley & MacFadyen 1999). The angular momentum needed is at least the value of the last stable orbit around a black hole of several solar masses, $j = 2\sqrt{3}GM/c = 4.6 \times 10^{16}(M_{BH}/3M_\odot)$ cm$^2$ s$^{-1}$ for a non-rotating hole and $j = 2/\sqrt{3}GM/c = 1.5 \times 10^{16}(M_{BH}/3M_\odot)$ cm$^2$ s$^{-1}$ for a spinning black hole with Kerr parameter $a = 1$. This compares with an angular momentum needed for the
millisecond 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 $3 \text{ M}_\odot$ is greater than that at $1.5 \text{ M}_\odot$, the minimum angular momentum requirements of the collapsar and millisecond magnetar models are comparable, though making a millisecond magnetar is clearly easier. Models exist that would give the necessary angular momentum for either (Section 10.3.2) in a star that has lost its hydrogen envelope before dying.

Two other necessary conditions for the collapsar model are that the star not explode prematurely truncating black hole formation, and that the jet, once produced, escapes the star. Considerable progress has been made exploring the second requirement. Calculations (Aloy et al. 2000; Zhang et al. 2004) have shown that an energy-loaded relativistic jet injected near the center of a massive star will penetrate the star and produce a streaming jet with the necessary Lorentz factor and opening angle to make an LSB. The distribution of jet energy with angle may depend upon the mass of the progenitor star with more massive progenitors having broader jets (Mizuta & Aloy 2009). In calculations so far, the energy loading was assumed to be thermal and the calculation ignored magnetic fields, but more recent calculations of Poynting flux jets show that they too can achieve a large terminal Lorentz factor (Tchekhovskoy et al. 2008). This is important since many calculations (Komissarov 2001) now show that the Blandford-Znajek (1977) mechanism, and other MHD processes (Komissarov 2001; McKinney et al. 2004; Hawley & Krolik 2006) are probably the origin of relativistic jets. These mechanisms work well in the context of the collapsar model (Barkov & Komissarov 2008; Tchekhovskoy et al. 2008), but the jets are Poynting dominated. Neutrino annihilation as originally discussed in (MacFadyen & Woosley 1999; Popham et al. 1999) is probably not adequate (Nagataki et al. 2007) or at least not as important as MHD processes (McKinney 2005a) in driving jets. The relative contributions of neutrinos and MHD processes may depend on the black hole mass, spin rate, and accretion rate though. For black holes larger than a few $\text{M}_\odot$, neutrino annihilation is probably not a major effect. For lower masses, hybrid models may exist in which neutrino annihilation helps boost or initiate an MHD jet. It may also be that the jet is more thermal in nature while it stays inside the star, but more MHD like after the polar axis has been evacuated.

In addition to the jet itself, the “disk wind” (MacFadyen & Woosley 1999; Kohri et al. 2005; McKinney & Nareayan 2007; Barkov & Komissarov 2008) plays an important role in the collapsar model and shows promise of providing the $\sim 10^{51} \text{ erg}$ of energy input to a large solid angle needed to blow
up the star and to make the necessary $^{56}$Ni (MacFadyen & Woosley 1999; Nagataki et al. 2007). It is important to note here that the properties of the supernova that accompanies an LSB are given by the disk wind, not the jet itself. The explosion energy and brightness of the supernova are, to some extent, decoupled from the properties of the burst. By disk wind here, we also mean to include the funnel of subrelativistic mass ejection surrounding the jet in the black-hole spin powered model.

There is thus no compelling reason why the LSB jet energy, the supernova kinetic energy, or the $^{56}$Ni yield should be a constant. Faster rotating black holes may accelerate relativistic jets more efficiently. Hawley & Krolik (2006) estimate the efficiency for producing the jet scales as $0.002/(1 - a)$ with $a$ the Kerr parameter (see also McKinney 2005b). For accretion rates of $0.01 \, M_\odot \, s^{-1}$ and $a = 0.9$, this is about $4 \times 10^{50} \, \text{erg} \, s^{-1}$. Given that lower metallicity progenitors end up with more rapidly rotating cores, this efficiency factor suggests stronger bursts at lower metallicity. Hawley & Krolik also calculate that a substantial fraction of the accretion energy ends up in a funnel-like sub-relativistic outflow surrounding the jet. This plus the disk wind may be important to the dynamics of the supernova.

One also expects the power of the burst to depend on the duration and rate of accretion. For a simple dipole case, the efficiency of extracting black hole rotational energy may go as $\dot{M}^{1/2}$ (Haley & Krolik 2006), and of course accreting more total mass will make more energy. This again favors more massive stars with higher rotation rates (so that more of the star forms a disk). It has been suggested that collapsars with low accretion rate make less $^{56}$Ni (Lopez-Camara et al. 2008).

A severe concern for the collapsar model though is the poorly explored formation process for the black hole in a situation where enough rotation exists to form a disk. As with magnetar birth, this is a hard problem involving neutrino physics, MHD, high density physics, and general relativity all coupled to three-dimensional hydrodynamics. A preliminary attempt has been made by Dessart et al. (2008) who conclude, for conditions where the collapsar is expected to work, that a magneto-rotational instability (MRI) may blow up the star before a black hole is formed. Their results are sensitive to an approximate treatment of the magnetic field evolution though (Etienne et al. 2006). Using the field of the actual pre-supernova model, they do make a black hole. Using a field that they postulate would be created by a well resolved MRI, they get a powerful explosion. It is also troubling that the MRI that plays such a dominant role in the collapse is completely ignored in the stellar evolution just before the collapse. With such powerful radial fields, $B_r \sim B_\phi$, the core would rotate more slowly. In fact, since
their model uses most of its energy making a supernova little is left to make an LSB jet by any mechanism. Still this is a troubling gap in an otherwise successful model.

10.5 A diverse set of phenomena
Given that the death of a massive star, with variable mass, angular momentum, and structure, somehow, sometimes creates a powerful jet near its center, a great variety of phenomena are possible. The LSBs and X-ray flashes studied so far may just be the most easily recognized consequences.

10.5.1 Core-collapse supernovae
Polarization data suggest the breaking of spherical symmetry in all types of core-collapse supernovae (Wang & Wheeler 2008). For Type II supernovae, the deformation becomes greater as one peers, with time, deeper into the explosion. This does not necessarily imply that the typical supernova explosion is powered by rotation, but it does imply strong symmetry breaking either during or shortly after the explosion. This symmetry breaking could be due to the rotation of the neutron star, vibrational energy input by asymmetric fallback, or accretion instabilities during fallback (Scheck et al. 2006; Blondin & Mezzacappa 2007; Burrows et al. 2007a). In the future, it will be important to understand the full continuum of massive star death. Are LSBs a separate phenomenon or, as seems more likely, just the extremity of a distribution of asymmetric supernova explosions? What are the necessary mass and rotation rate of stars for which rotation is the dominant source of explosion energy? Numerical simulation may resolve this issue in the next decade.

10.5.2 Magnetar birth
Magnetars with field strengths $10^{14}$ to $10^{15}$ Gauss exist and may be formed in the birth of 10% of all neutron stars (Kouveliotou 1998). This is far too many for every magnetar birth to produce an LSB. What do the rest look like? Recently, it has been suggested (Woosley 2009; Kasen & Bildsten 2010) that the emission of young magnetars might power the light curves of many kinds of supernovae, including ultra-luminous ones and perhaps some of the supernovae associated with LSBs. Interestingly, the magnetars with the strongest fields spin down the quickest and contribute less to the later light curve. Finding just one supernova whose light curve is unambiguously
Fig. 10.1. Three-dimensional calculation by Weiqun Zhang of a relativistic jet of $3 \times 10^{48}$ erg s$^{-1}$ introduced at $1 \times 10^{10}$ cm in a 15 $M_\odot$ Wolf-Rayet presupernova star of radius $8 \times 10^{10}$ cm. 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 $3 \times 10^{50}$ 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.

due to magnetar energy deposition would strengthen the case for magnetar involvement in LSBs. Unfortunately, unique diagnostics may be hard to find. The very late time light curve might distinguish between a $^{56}$Ni power source and a pulsar in a Type Ibc supernova. There may also be spectroscopic differences depending on how the magnetar deposits its energy.

10.5.3 Weak jets and suffocated jets

There is a minimum power that the central engine must provide for a relativistic jet to escape in a reasonable time, even in a hydrogen-stripped massive star. Figure 1 (Woosley & Zhang 2007) shows the density structure just as a jet of $3 \times 10^{48}$ erg s$^{-1}$ jet erupts from the surface of the star 27 s after initiation. Two other higher energy jets, 0.3 and $3 \times 10^{50}$ erg s$^{-1}$ took 15 s and 7 s respectively. While a relativistic jet of arbitrarily low power will eventually break out of any star, the stellar structure will have changed and the central engine may have turned off. Highly relativistic jets might, in some cases, _never_ emerge from the star ("failed GRB"). Such jets
Models for Gamma-ray Burst Progenitors and Central Engines

could, however, deliver considerable energy focused on a small solid angle of the stellar surface. The same fate would await a powerful jet that did not maintain its orientation at the center to within a few degrees (Zhang et al. 2004). Depending on how close to the surface the jet makes it before dissipating, one could have either a mildly asymmetric supernova with essentially no relativistic ejecta, or a weak LSB powered by shock breakout (Tan et al. 2001) or collision with circumstellar matter (Wang et al. 2007; Katz et al. 2009). Perhaps this occurred in GRB 980425.

10.5.4 Shock breakout

Even the breakout of a spherically symmetric shock in an ordinary \(10^{51}\) erg Type Ib supernova will produce a soft X-ray transient (Colgate 1968; Blinnikov et al. 2003). Such a transient was observed (Soderberg et al. 2008) for Type Ib SN 2008D. Its duration, \(\sim 400\) s in the 0.3 - 10 keV band, was much longer than anticipated on the basis of previous models. Soderberg et al. (2008) attributed the long time scale to circumstellar interaction. Others invoked a mildly relativistic jet energized by black hole formation (Mazzali et al. 2008), wind interaction, or an extended radius for the progenitor (Chevalier & Fransson 2008). Evidence for the latter interpretation comes from recent studies (Yoon et al. 2010) that show Type Ib progenitors in binaries have considerably larger radii than previously expected. Hopefully, a large number of these events will be discovered in the supernova surveys planned for the next decade. While not GRBs themselves, they may help to elucidate the physics of shock breakout in compact progenitors similar to those where GRBs occur.

10.5.5 “Gamma-ray bursts” with low luminosity and long duration

If only the matter near the surface of the star has enough angular momentum to form a disk outside a black hole, a longer fainter transient could still be produced. The physics of jet production would be similar to other collapsars, but the collapse time scale would be longer. Most of the binary models proposed for LSBs give a surface with high angular momentum, but do not speed up the core (Section [10.5.2]). Chemically homogeneous evolution including magnetic torques frequently gives helium cores in which only the outer layers can form a disk (Woosley & Heger 2006). Even some models that make red and blue supergiants have enough rotation in their outer envelope to make a disk, unless the mass loss rate is high (Section [10.5.7]). Despite
a similar central engine, the emerging jets might have different properties because of the lower accretion rate, larger black hole mass, and the fact that the jet has little or no star left to penetrate. The most luminous of these transients, in which roughly a solar mass accreted from the surface of a Wolf-Rayet progenitor with about a solar radius, would have a duration in its rest frame of several minutes and a luminosity similar to (weaker) LSBs (e.g., Janiuk & Proga 2008). In progenitors that are giants however, the time scale could be days and the event might resemble a blazar or ultra-luminous X-ray source more than an LSB (see also Section 10.5.7). The total energy in the event would be comparable to LSBs, $\sim 10^{51}$ erg. Any accompanying supernova would be faint (Lopez-Camara et al. 2008) unless the star were a giant.

### 10.5.6 Off-axis phenomena

LSBs require relativistic jets for their production and this means that what an observer sees will be strongly biased by their location. For a jet with sharp boundaries, the emission intensity falls off rapidly with viewing angle (Granot et al. 2002, 2005; Ramirez-Ruiz et al. 2005), but such sharp boundaries are unrealistic. There will thus be emission as the cocoon of the jet breaks through the stellar photosphere (e.g., Ramirez-Ruiz et al. 2002; Zhang et al. 2003, 2004) and due to the interaction of the cocoon with the circumstellar medium. Such interactions might give rise to X-ray flashes (Chapter 4; Pe‘er et al. 2006) or enhanced X-ray emission in an LSB (Peng et al. 2005; Butler 2007; Ghisellini et al. 2007).

### 10.5.7 Pair-instability supernovae

SN 2006gy and SN 2007bi have demonstrated that stars with helium cores of at least 45 $M_\odot$, and perhaps over 100 $M_\odot$ are dying, even in the modern Universe (Smith et al. 2007; Woosley et al. 2007; Gal-Yam et al. 2009). Such stars encounter the pair-instability, first as a violent pulsational instability for helium cores in the mass range $M_{\text{He}} = 40 - 60 M_\odot$ (main sequence masses from 95 to 130 $M_\odot$), and then as a violent explosive instability that disrupts the entire star for $M_{\text{He}} = 60 - 133 M_\odot$ (main sequence masses from 130 to 260 $M_\odot$). Above 260 $M_\odot$ black holes are formed after helium depletion. These numbers are for non-rotating stars of constant mass (Woosley et al. 2007; Heger & Woosley 2002; Heger et al. 2003). For rotating stars, the relevant mass ranges are reduced.

Both pulsational pair instability supernovae (Section 10.5.8) and stars
over $260\,M_\odot$ are likely to make black holes. Fryer et al. (2001) studied the collapse of a $300\,M_\odot$ star, but assumed a rotating progenitor in which magnetic torques had been ignored in the pre-collapse evolution. Even with an extended hydrogen envelope, the helium core in this case maintained a specific angular momentum, $j \sim 10^{18}\,\text{cm}^2\,\text{s}^{-1}$, enough to form an accretion disk before the entire helium core went inside the event horizon. Based upon an estimate of the viscous time scale for the disk, Fryer et al. (2001) estimated a transient of order 10 s duration in the rest frame, but speculated that it could be much longer.

No calculations have been published of progenitor evolution in this mass range that include magnetic torques, but unpublished studies of a $250\,M_\odot$ model with metallicity $10^{-4}$ solar (Woosley 2010) show that a variety of outcomes are possible. The results depend upon the rotation rate assumed and the way magnetic torques and mixing at the boundaries of convective regions are treated. For the same physics as in Woosley & Heger (2006), three models were studied with total angular momentum $J = 0.75, 1.0$ and $1.5 \times 10^{54}\,\text{erg}\,\text{s}$ corresponding to equatorial rotation speeds on the main-sequence of $170\,\text{km}\,\text{s}^{-1}$, $220\,\text{km}\,\text{s}^{-1}$, and $305\,\text{km}\,\text{s}^{-1}$. These stars died with helium core masses of 142, 166, and $222\,M_\odot$, so all three made black holes. However, all stars were supergiants in their late stages and, because of the magnetic torques, their helium cores ended up rotating about an order of magnitude slower ($j \sim 10^{16-17}\,\text{cm}^2\,\text{s}^{-1}$) than in the previous study. Consequently the entire helium core and most of the hydrogen envelope would collapse into the hole promptly in all three cases without making a disk. However, the angular momentum extracted from the core increased that of the hydrogenic envelope. The specific angular momentum in the outer 20 – 40$M_\odot$ exceeded $10^{18}\,\text{cm}^2\,\text{s}^{-1}$ in all models. In the outer 10$M_\odot$ it even exceeded $10^{19}\,\text{cm}^2\,\text{s}^{-1}$, sufficiently high to form a disk.

This matter is at large radius and low density, so its free fall time scale is roughly $10^4$ to $10^5$ s. If it is not lost from the star prior to the collapse, the outer solar mass, with $j \sim 10^{20}\,\text{cm}^2\,\text{s}^{-1}$ would become supported by rotation at $3 \times 10^{11}\,\text{cm}$ with an orbital period of $\sim 1000$ s. Depending upon disk viscosity, it might take a day to fall in. An accretion rate of 1 $M_\odot$ day$^{-1}$ with an efficiency for mass to energy conversion of 10% would give a luminosity of $10^{48}\,\text{erg}\,\text{s}^{-1}$, even without beaming. A similar model was recently discussed by Komissarov and Barkov (2010).
10.5.8 Pulsational pair supernovae

Pulsational pair-instability supernovae eject solar masses of material in repeated supernova-like outbursts with intervals that can span days to centuries (Woosley et al. 2007) before finally collapsing to a neutron star or a black hole. The variable intervals and masses ejected allow the possibility of a wide range of observed phenomena. Because of their short lifetimes, the iron core in these stars, which may exceed 2 or even 3 $M_\odot$, remains rapidly rotating. Black hole formation seems likely, but even if it is avoided, the rapid rotation would produce a millisecond magnetar. In most cases, any jet produced would dissipate its relativistic energy while still buried in optically thick ejecta. In some cases, though, primarily those on the lighter end of the mass scale, the interval between shell ejection is long enough that an LSB could happen inside a previous supernova. The “supranova” model (Vietri & Stella 1998) in which an LSB can happen inside of a supernova that occurred years before is, in some sense, still with us.

10.5.9 Short hard bursts and bursts at high redshift

One of the major goals of GRB astronomy has been the discovery of events with very high redshifts. This is motivated both by the desire to find evidence for massive star death in the early Universe, and by the belief that the first and second generation stars in the Universe may have had unusual properties. In particular, they might have had high mass, low metallicity, and rapid rotation, just the sorts of things that favor LSBs. Earlier this decade, it was hoped that one might find luminous GRB counterparts to pair-instability supernovae (Fryer et al. 2001). That still could happen, but as argued in Section 10.5.7, that sort of star death now seems more likely to produce long transients with low luminosity.

What has been found instead is confusing. GRB 050904, one of the more distant bursts discovered ($z = 6.3$) had a duration ($T_{90}$) of 220 s (Cusumano et al. 2006, 2007) with flaring activity that lasted one to two hours. The total energy in relativistic ejecta was $\sim 10^{52}$ erg (Frail et al. 2006). In addition, GRB 050730 at $z = 3.969$, GRB 050505 at $z = 4.27$, and GRB 050814 at $z = 5.3$ were all exceptionally long lasting and among the brightest GRBs ever observed (Cusumano et al. 2007). So the case was starting to look good for very energetic LSBs at high redshift (Section 10.3.3). But then came GRB 080913 (Greiner et al. 2009) and GRB 090423 (Tanvir et al. 2009; Salvaterra et al. 2009), the two most distant GRBs to date, at redshifts 6.7 and 8.2 respectively. By their observed durations, these events would be classified as LSBs, but it was noted that in their frame, the duration ($T_{90}$)
of each was less than 2 s and their prompt emission was hard; therefore it was argued that they belong to the SHB class. However, one should remember that the LSB/SHB classification scheme is based on observer-frame duration distribution, according to which they are clearly LSBs. These GRBs also exhibited post-burst X-ray flaring activity with energy comparable to the initial burst. Indeed, a more general discussion is developing about a group of bursts, near and far, that straddle the boundary between LSBs and SHBs according to various old, and new, criteria (Perley et al. 2009; Zhang et al. 2009).

One possibility is that we are witnessing the breakdown, or at least substantial modification of the highly successful internal-shock model (Rees & Mészáros 1994) for GRBs. It has become common, without really good cause even in the internal-shock model, to associate the duration of a burst, especially $T_{90}$, with the activity cycle of its central engine, i.e., merging compact objects for short bursts and massive star death for long ones, with a dividing line at 2 s. Perhaps in the very high redshift bursts and other energetic short bursts, internal shocks are less efficient or have a different characteristic time scale (Zhang et al. 2009). Zhang et al. (2003) have also discussed the possibility of producing short bursts in massive stars by an external shock mechanism in the medium just outside the star, and Waxman et al. (2003) have also discussed SHBs as a break out phenomenon. Finally, the emission of a Poynting flux jet as it erupts from the surface of a star has yet to be calculated, and may be quite different from the later emission after the jet has cleared a broad passage through the star. If the prompt emission is really just some sort of break out transient, the distant bursts from long ago may end up telling us about interesting variations in the massive stellar progenitor properties - how they collimate and modulate jets and their circumstellar densities - but may not help to discriminate the “central engine”. An exception would be if an event were discovered that had a total energy beyond what a magnetar can provide.

**10.6 Possible model diagnostics**

**10.6.1 The maximum energy of the explosion**

The minimum rotational period of a rigidly rotating neutron star is near 1 ms (Lattimer & Prakash 2007). Because of the magneto-rotational instability, a differentially rotating neutron star is not likely to remain so for long, but this final rapid rotation rate can only be achieved after a several second long Kelvin-Helmholtz evolution of the neutron star. During this time, magnetic torques and jets may appreciably dissipate the rotation (Dessart et al. 2008).
As a result, the maximum rotational energy available to explode a supernova and power an LSB in the magnetar model is probably only a few times $10^{52}$ erg (Ott et al. 2006; Burrows et al. 2007b), and Adam Burrows, private communication). This is smaller than the kinetic energies inferred in some models for “hypernovae” (e.g., Maeda & Nomoto 2003), but these limits from one-dimensional models are not precise. Collapsars can, in principle, provide a much larger energy, up to a substantial fraction of the rotational energy of a Kerr hole or the accretion energy of several solar masses, both $\sim 10^{54}$ erg. In the common case, a smaller value is expected. The highest current lower limits are thus close to the maximum allowed in the magnetar model (Section 10.2.3), but are not yet in conflict.

### 10.6.2 $^{56}$Ni and supernovae

The magnetar model and collapsar model make their $^{56}$Ni in different ways - the magnetar by a shock wave, the collapsar by a disk wind. Both models are still rudimentary regarding the amount of $^{56}$Ni that is made. In the magnetar model, the same engine must produce: i) enough energy in a directed relativistic form, over an extended period of time, to power the burst; ii) enough nearly isotropic energy to blow up the star; and iii) at least occasionally, a few tenths of a solar mass of $^{56}$Ni to make the supernova bright. The latter requires depositing at least several times $10^{51}$ erg in a large solid angle in much less than one second in order to heat sufficient matter above $5 \times 10^{9}$ K. So far, the published magnetar models relegate the $^{56}$Ni problem to some precursor explosion that sets up the circumstances for the magnetar to operate.

Still, it might be possible to thread this needle. There are several relevant time scales in the magnetar model. First is the time required to dissipate the differential rotation of the proto-neutron star. This involves magnetic field generation and instabilities and could be short compared with the Kelvin-Helmholtz timescale (Dessart et al. 2008). Depending upon how and where this energy is dissipated, starting from a rigidly rotating iron core, there is enough energy in differential rotation alone to power the supernova and make the necessary $^{56}$Ni. The other time scales are the Kelvin-Helmholtz time scale, during which the neutron star reaches its terminal rotation speed, and the uncertain time scales for spin down and accretion. The possibility of accretion is often overlooked in the magnetar model. If the proto-neutron star has too much angular momentum to be a millisecond pulsar, it may shed the excess in a disk that it later accretes on a viscous time scale. At that point, the model would resemble both the outcome of merging neutron
stars and the collapsar model, except that the disk mass would be small compared with the latter.

Given the possibilities, a magnetar model can probably be evolved that provides the necessary $^{56}\text{Ni}$ yield. Alternatively, the brightness of the supernova may not be due to radioactivity (Kasen & Bildsten 2010; Woosley 2009). Either way, additional data on the SN-LSB connection and more realistic theoretical models will be helpful. Given the difficulty making $^{56}\text{Ni}$ in the first place, a LSB without a bright supernova should not be difficult to arrange in the magnetar model, but an LSB with no supernova would be puzzling.

The collapsar model can also, in principle, make large amounts of $^{56}\text{Ni}$ and explode the star violently while still having plenty of enduring power for the burst. However, this all relies on the hydrodynamics of the disk wind which has been poorly explored in realistic models. It is certainly possible for it to make very little. The $^{56}\text{Ni}$ that is made could accrete onto the black hole during a “fall-back” phase. $^{56}\text{Ni}$ production might also be low in that variety of collapsar where the black hole itself is a result of fall-back (Fryer et al. 2007).

### 10.6.3 Continued activity of the central engine

*Swift* has seen “flares” of hard X-ray emission occurring hundreds to thousands of seconds after the main burst (Falcone et al. 2007; Chincarini et al. 2007). These resurgences of emission, which can sometimes contain as much energy as the principal burst (but more typically $\sim10\%$), are generally taken to be evidence of continuing activity of the central engine. Flare durations are often quite short compared with the elapsed time since the burst onset and their spectrum is harder than that of the underlying continuous emission.

Dai et al. (2006) have suggested that late flares can be explained by magnetic reconnection events driven by the breakout of magnetic fields from the surface of differentially rotating millisecond pulsars (see also Kluzniak & Ruderman 1998). Their model was suggested in the context of short hard bursts, but might apply to the magnetar model for long bursts as well. Giannios (2006) also suggested reconnection, but in the ejecta themselves, placing the origin far from the source. However, both these explanations must confront the fact that the flares have observational properties that are very similar to the prompt emission (Krimm et al. 2007; Margutti et al. 2010).

An alternate explanation, and one perhaps more favorable for the more
energetic flares, is transient accretion (King et al. 2005; Lazzati et al. 2008; Kumar et al. 2008). Fallback can continue from the supernova that accompanies the LSB at an appreciable rate for hours after the initial burst (MacFadyen et al. 2001; Kumar et al. 2008; Zhang et al. 2008) and may be unsteady. Unpublished 2D collapsar calculations by Weiqun Zhang, sometimes show an oscillatory cycle in which a weak equatorial explosion is launched by energy released in the disk. Material moves out for a time, shutting off the accretion, then falls back in again re-establishing the disk. The natural time scale for these cycles is roughly the dynamic time for the helium core, $\sim 100$ s, but wide variations are possible. One might expect such oscillations to be more prominent in very massive stellar cores that are hard to unbind.

Acknowledgements

This work has been supported by the NASA Theory Program (NNG05GG08G and NNX09AK36G). The author thanks Chryssa Kouveliotou and Ralph Wijers for their perseverance in assembling this volume and Ralph for a careful reading and editing of the manuscript. Adam Burrows and Weiqun Zhang provided important unpublished details of their models.

References

Abbott, B., et al. (2008). ApJ, 681, 1419.
Abdo, A.A., et al. (2009). Science, 323, 1688.
Aloy, M.A., Müller, E., Ibáñez, J.M., Martí, J.M., & MacFadyen, A. (2000). ApJ, 531, L119.
Baade, W., & Zwicky, F. (1934). PR, 46, 76.
Barkov, M. V., & Komissarov, S. S. (2008). MNRAS, 385, L28.
Bissaldi, E., Calura, F., Matteucci, F., Longo, F., & Barbiellini, G. (2007). A&A, 471, 585.
Blandford, R. D., & Znajek, R. L. (1977). MNRAS, 179, 433.
Blinnikov, S., Chugai, N., Lundqvist, P., Nadyozhin, D., Woosley, S., & Sorokina, E. (2003, From Twilight to Highlight: The Physics of Supernovae, 23.
Blondin, J. M. & Mezzacappa, A. (2007). Nat, 445, 58.
Braithwaite, J. (2006). A&A, 453, 687.
Braithwaite, J. (2008). MNRAS, 386, 1947.
Bucciantini, N., Quataert, E., Arons, J., Metzger, B. D., & Thompson, T. A. (2008). MNRAS, 383, L25.
Bucciantini, N., Quataert, E., Metzger, B. D., Thompson, T. A., Arons, J., & Del Zanna, L. (2009). MNRAS, 396, 2038.
Buras, R., Janka, H.-T., Rampp, M., & Kifonidis, K. (2006). A&A, 457, 281.
Burrows, A., Livne, E., Dessart, L., Ott, C. D., & Murphy, J. (2007a). ApJ, 655, 416.
Burrows, A., Dessart, L., Livne, E., Ott, C. D., & Murphy, J. (2007b). ApJ, 664, 416.
Butler, N. R. (2007). ApJ, 656, 1001.
Campana, S., et al. (2008). ApJ, 683, L9.
Cantiello, M., Yoon, S.-C., Langer, N., & Livio, M. (2007). A&A, 465, L29.
Cenko, S. B., et al. (2010a). ApJ, 711, 641.
Cenko, S. B., et al. (2010b). arXiv:1004.2900
Chandra, P., et al. (2008). ApJ, 683, 924.
Charbonnel, C., & Talon, S. (2005). Science, 309, 2189.
Chen, H.-W., et al. (2009). ApJ, 691, 152.
Christensen, L., Hjorth, J., & Gorosabel, J. (2004). A&A, 425, 913.
Colgate, S. A., & White, R. H. (1966). ApJ, 143, 626.
Colgate, S. A., (1968). Canadian J. Phys. 46, 476.
Covino, S., et al. (2006). A&A, 447, L5.
Cusumano, G., et al. (2007). A&A, 462, 73.
Dai, Z. G., Wang, X. Y., Wu, X. F., & Zhang, B. (2006) Science, 311, 1127.
Davies, B., Figer, D. F., Kudritzki, R.-P., Trombley, C., Kouveliotou, C., & Wachter, S. (2009). ApJ, 707, 844.
Denissenkov, P. A., & Pinsonneault, M. (2007). ApJ, 655, 1157.
Dessart, L., Burrows, A., Livne, E., & Ott, C. D. (2008). ApJ, 673, L43.
Duncan, R. C., & Thompson, C. (1992). ApJ, 392, L9.
Duncan, R. C., & Thompson, C. (1996), High Velocity Neutron Stars, 366, 111.
Ekström, S., Meynet, G., Maeder, A., & Barblan, F. (2008). A&A, 478, 467.
Etienne, Z. B., Liu, Y. T., & Shapiro, S. L. (2006). PRD, 74, 044030.
Falcone, A. D., et al. (2007). ApJ, 671, 1921.
Fiore, F., Guetta, D., Piranomonte, S., D’Elia, V., & Antonelli, L. A. (2007). A&A, 470, 515.
Firmani, C., Avila-Reese, V., Ghisellini, G., & Tutukov, A. V. (2004, ApJ, 611, 1033.
Frary, D. A., et al. (2001). ApJ, 562, L55.
Frary, D. A., et al. (2006). ApJ, 646, L99.
Fruchter, A. S., et al. (1999). ApJ, 519, L13.
Fruchter, A. S., et al. (2006). Nat, 441, 463.
Fryer, C. L. (1999). ApJ, 522, 413.
Fryer, C. L., Woosley, S. E., Herant, M., & Davies, M. B. (1999). ApJ, 520, 650.
Fryer, C. L., Woosley, S. E., & Heger, A. (2001). ApJ, 550, 372.
Fryer, C. L., Hungerford, A. L., & Young, P. A. (2007). ApJ, 662, L55.
Fynbo, J. P. U., et al. (2003). A&A, 406, L63.
Gal-Yam, A., et al. (2009). Nat, 646, 624.
Georgy, C., Meynet, G., & Maeder, A. (2008). Proceeding of the IAU Symposium 255, astro-ph/0807.5061.
Ghisellini, G., Ghirlanda, G., & Tavecchio, F. (2007). MNRAS, 375, L36.
Giammar, D. (2006, A&A, 455, L5.
Gill, R. & Heyl, L. (2007). MNRAS, 381, 52.
Gorosabel, J., et al. (2005). A&A, 444, 711.
Granot, J., Panaitescu, A., Kumar, P., & Woosley, S. E. (2002). ApJ, 570, L61.
Granot, J., Ramirez-Ruiz, E., & Perna, R. (2005). ApJ, 630, 1003.
Greiner, J., et al. (2009). ApJ, 693, 1610.
Harrison, F. A., et al. (1999). ApJ, 523, L121.
Hawley, J. F., & Krolik, J. H. (2006). ApJ, 641, 103.
Heger, A., Langer, N., & Woosley, S. E. (2000). ApJ, 528, 368.
Heger, A., & Woosley, S. E. (2002). *ApJ*, **567**, 532.
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. (2003). *ApJ*, **591**, 288.
Heger, A., Woosley, S. E., & Spruit, H. C. (2005). *ApJ*, **626**, 350.
Hirschi, R., Meynet, G., & Maeder, A. (2005). *A&A*, **443**, 581.
Hjorth, J., et al. (2003). *Nat*, **423**, 847.
Höflich, P., Wheeler, J. C., & Wang, L. (1999). *ApJ*, **521**, 179.
Ivanova, N., Podsiadlowski, Ph., & Spruit, H (2002) *MNRAS*, **334**, 819.
Jakobsson, P., et al. (2006). *A&A*, **447**, 897, see also [http://raunvis.hi.is/~pja/GRBsample.html](http://raunvis.hi.is/~pja/GRBsample.html).
Janiuk, A., & Proga, D. (2008). *ApJ*, **675**, 519.
Janka, H.-T., Langanke, K., Marek, A., Martínez-Pinedo, G., Müller, B. (2007). *Phys. Rept.*, **442**, 38.
Joss, P. C., & Becker, J. A. (2007). Massive Stars in Interactive Binaries, **367**, 517.
Kalogera, V., et al. (2004). *ApJ*, **601**, L179 and **614**, L137.
Kamble, A., et al. (2009). Astronomical Society of the Pacific Conference Series, **407**, 295.
Kaneko, Y., et al. (2007). *ApJ*, **654**, 385.
Kasen, D., & Bildsten, L. (2010). *ApJ*, **717**, 245.
Katz, B., Budnik, R., & Waxman, E. (2009). [arXiv:0902.4708](http://arxiv.org/abs/0902.4708).
Kelly, P. L., Kirshner, R. P., & Pahre, M. (2008). *ApJ*, **687**, 1201.
King, A., O’Brien, P. T., Goad, M. R., Osborne, J., Olsson, E., & Page, K. (2005). *ApJ*, **630**, L113.
Kluźniak, W., & Ruderman, M. (1998). *ApJ*, **505**, L113.
Kocevski, D., & Butler, N. (2008). *ApJ*, **680**, 531.
Kohri, K., Narayan, R., & Piran, T. (2005). *ApJ*, **629**, 341.
Komissarov, S. S. (2001). *MNRAS*, **326**, L41.
Komissarov S. S., Barkov M. V., (2008). *MNRAS*, **382**, 1029.
Komissarov, S. S., & Barkov, M. V. (2010). *MNRAS*, **402**, L25.
Kouveliotou, C., Meegan, C. A., Fishman, G. J., Bhat, N. P., Briggs, M. S., Koshut, T. M., Paciesas, W. S., & Pendleton, G. N. (1993). *ApJ*, **413**, L101.
Kouveliotou, C., et al. (1998). *Nat*, **393**, 235.
Kulkarni, S. R., et al. (1999). *Nat*, **398**, 389.
Krimm, H. A., et al. (2007). *ApJ*, **665**, 554.
Kumar, P., Narayan, R., & Johnson, J. L. (2008) *Science*, **321**, 376.
Langer, N., (1992). *A&A*, **265**, L17.
Langer, N., & Norman, C. A. (2006). *ApJ*, **638**, L63.
Larsson, J., Levan, A. J., Davies, M. B., & Fruchter, A. S. (2007). *MNRAS*, **376**, 1285.
Lattimer, J. M., & Prakash, M. (2007). *Phys. Rept.*, **442**, 109.
Lazzati, D., Perna, R., & Begelman, M. C. (2008). *MNRAS*, **388**, L15.
Li, X.-D. (2003). *ApJ*, **596**, L199.
Li, Z.-Y. & Chevalier, R. A. (1999). *ApJ*, **526**, 716.
Liu, J., McClintock, J. E., Narayan, R., Davis, S. W., & Orosz, J. A. (2008). *ApJ*, **679**, L37.
Lopez-Camara, D., Lee, W. H., & Ramirez-Ruiz, E. (2009). *ApJ*, **692**, 804.
MacFadyen, A. I., & Woosley, S. E. (1999). *ApJ*, **524**, 262.
MacFadyen, A. I., Woosley, S. E., & Heger, A. (2001). *ApJ*, **550**, 410.
Maeda, K., & Nomoto, K. (2003). *ApJ*, **598**, 1163.
Maeder, A., (1987). *A&A*, **178**, 159.
Maeder, A. & Meynet, G. (2001). *A&A*, 373, 555.
Margutti, R., Guidorzi, C., Chincarini, G., Bernardini, M. G., Genet, F., Mao, J., & Pasotti, F. (2010). *Astronomy & Astrophysics*, 512, A80.
Martayan, C., Frémat, Y., Hubert, A.-M., Floquet, M., Zorec, J., & Neiner, C. (2007). *A&A*, 462, 83.
Mazets, E. P., et al. (2008). *ApJ*, 680, 545.
Mazzali, P. A., et al. (2008.) *Science*, 321, 1185.
McClintock, J. E., Shafee, R., Narayan, R., Remillard, R. A., Davis, S. W., & Li, L.-X. (2006). *ApJ*, 652, 518.
McClintock, J. E., Narayan, R., & Shafee, R. (2007, arXiv:0707.4492 to appear in Black Holes, eds. M. Livio and A. Koekemoer (Cambridge University Press).
McKinney, J. C., & Gammie, C. F. (2004). *ApJ*, 611, 977.
McKinney, J. C. (2005a). *Astronomy & Astrophysics*, 436, L11.
McKinney, J. C. (2005b). *ApJ*, 630, L5.
McKinney, J. C., & Narayan, R. (2007). *MNRAS*, 375, 531.
Messer, O. E. B., Bruenn, S. W., Blondin, J. M., Hix, W. R., & Mezzacappa, A. (2008). *Journal of Physics Conference Series*, 125, 012010.
Meynet, G. and Maeder, A. (2007). *A&A*, 464, L11.
Mizuta, A., & Aloy, M. A. (2009). *ApJ*, 699, 1261.
Modjaz, M., et al. (2008). *AJ*, 135, 1136.
Muno, M. P., Gaensler, B. M., Necita, A., Miller, J. M., & Slane, P. O. (2008). *ApJ*, 680, 639.
Muno, M. P., et al. (2006). *ApJ*, 636, L41.
Muno, M. (2008). 37th COSPAR Scientific Assembly. Held 13-20 July (2008, in Montréal, Canada., 37, 2136.
Nagataki, S., Takahashi, R., Mizuta, A., & Takiwaki, T. (2007). *ApJ*, 659, 512.
Nakar, E. (2007). *Phys. Rept.*, 442, 166.
Nissen, P. E., Primas, F., Asplund, M., & Lambert, D. L. (2002). *A&A*, 390, 235.
Nomoto, K., Maeda, K., Tominaga, N., Okhobo, T., Deng, J., & Mazzali, P. A. (2005). *Ap. & Spac. Sci.*, 298, 81.
Nomoto, K., Tanaka, M., Tominaga, N., Maeda, K., & Mazzali, P. A. (2007). to appear in New Astronomy Reviews, Proceedings of the Conference *A Life with Stars*, astroph-0707.2219.
Oppenheimer, J. R., & Volkoff, G. M. (1939). *Phys. Rev.*, 55, 374.
Orosz, J. A., et al. (2007). *Nat*, 449, 872.
Östlin, G., Zackrisson, E., Sollerman, J., Mattila, S., & Hayes, M. (2008). *MNRAS*, 387, 1227.
Ostriker, J. P., & Gunn, J. E. (1971). *ApJ*, 164, L95.
Ott, C. D., Burrows, A., Thompson, T. A., Livne, E., & Walder, R. (2006). *ApJS*, 164, 130.
Papar, D. M., et al. (2005). *Nat*, 434, 1107.
Paragi, Z., et al. (2010). *Nat*, 463, 516.
Pe'er, A., Mészáros, P., & Rees, M. J. (2006). *ApJ*, 652, 482.
Peng, F., Königl, A., & Granot, J. (2005). *ApJ*, 626, 966.
Penny, L. R., Sprague, A. J., Seago, G., & Gies, D. R. (2004). *ApJ*, 617, 1316.
Perley, D. A., et al. (2009). *ApJ*, 696, 1871.
Petrovic, J., Langer, N., Yoon, S.-C., & Heger, A. (2005). *A&A*, 435, 247.
Petrovic, J. (2006). Publications de l’Observatoire Astronomique de Beograd, 80, 57.
Popham, R., Woosley, S. E., & Fryer, C. (1999). *ApJ*, 518, 356.
Prochaska, J. X., et al. (2006). *ApJ*, 642, 989.
Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. (2008). *American Institute of Physics Conference Series*, 1000, 479.
Ramirez-Ruiz, E., Celotti, A., & Rees, M. J. (2002). *MNRAS*, 337, 1349.
Ramirez-Ruiz, E., Granot, J., Kouveliotou, C., Woosley, S. E., Patel, S. K., & Mazzali, P. A. (2005). *ApJ*, 625, L91.
Raskin, C., Scannapieco, E., Rhoads, J., & Della Valle, M. (2008). *ApJ*, 689, 358.
Rees, M. J., & Meszaros, P. (1994). *ApJ*, 430, L93.
Rhoads, J. E. (1999). *ApJ*, 525, 737.
Salvaterra, R., et al. (2009). *Nat*, 461, 1258.
Savaglio, S., Glazebrook, K., & Le Borgne, D. (2009). *ApJ*, 691, 358.
Rees, M. J., & Meszaros, P. (1994). *ApJ*, 430, L93.
Rhoads, J. E. (1999). *ApJ*, 525, 737.
Salvaterra, R., et al. (2009). *Nat*, 461, 1258.
Savaglio, S., Glazebrook, K., & Le Borgne, D. (2009). *ApJ*, 691, 358.
Rees, M. J., & Meszaros, P. (1994). *ApJ*, 430, L93.
Rhoads, J. E. (1999). *ApJ*, 525, 737.
Salvaterra, R., et al. (2009). *Nat*, 461, 1258.
Woosley, S. E., Heger, A., & Weaver, T. A. (2002). Rev. Mod. Phys., 74, 1015.
Woosley, S. E., Zhang, W., & Heger, A. (2004). Gamma-Ray Bursts: 30 Years of Discovery, 727, 343.
Woosley, S. E., & Bloom, J. S. (2006). ARA&A, 44, 507.
Woosley, S. E., & Heger, A. (2006). ApJ, 637, 914.
Woosley, S. E., Blinnikov, S., & Heger, A. (2007). Nat, 450, 390.
Woosley, S. E., & Zhang, W. (2007). R. Soc. of London Phil. Trans. Ser. A 365, 1129.
Yoon, S.-C., & Langer, N. (2005). A&A, 443, 643.
Yoon, S.-C., Langer, N., & Norman, C. A. (2006). A&A, 460, 199.
Yoon, S.-C., Langer, N., Cantiello, M., Woosley, S. E., & Glatzmaier, G. A. (2008). IAU Symposium, 250, 231.
Yoon, S.-C., Woosley, S. E., & Langer, N. (2010). submitted to ApJ, arXiv:1004.0843
Yoshida, N., Omukai, K., Hernquist, L., & Abel, T. (2006). ApJ, 652, 6.
Zahn, J.-P., Brun, A. S., & Mathis, S. (2007). A&A, 474, 145.
Zhang, W., Woosley, S. E., & MacFadyen, A. I. (2003). ApJ, 586, 356.
Zhang, W., Woosley, S. E., & Heger, A. (2004). ApJ, 608, 365.
Zhang, W., Woosley, S. E., & Heger, A. (2008). ApJ, 679, 639.
Zhang, B., et al. (2009). ApJ, 703, 1696.