BINARY MERGER PROGENITORS FOR GAMMA-RAY BURSTS AND HYPERNOVAE

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ABSTRACT

The collapsar model, the now leading model for the engine behind gamma-ray bursts and hypernovae, requires that a star collapses to form a black hole surrounded by an accretion disk of high angular momentum material. The current best theoretical stellar models, however, do not retain enough angular momentum in the core of the star to make a centrifugally supported disk. In this paper, we present the first calculations of the helium star/helium star merger progenitors for the collapsar model. These progenitors invoke the merger of two helium cores during the common-envelope inspiral phase of a binary system. We find that in some cases, the merger can produce cores that are rotating 3–10 times faster than single stars. He star/He star gamma-ray burst progenitors have a very different redshift distribution than their single-star gamma-ray burst progenitors, and we discuss how gamma-ray burst observations can constrain these progenitors.

Subject headings: black hole physics — gamma rays: bursts — stars: neutron — supernovae: general

Online material: color figures

1. INTRODUCTION

The accurate localizations of long-duration gamma-ray bursts (GRBs) have led to an increasing set of data indicating that these phenomena are associated with the deaths of massive stars (see Zhang et al. 2004 for a review). Some of the most convincing evidence is the simultaneous (both spatially and temporally) occurrence of a GRB (GRB 030329) with a bright, energetic Type Ic supernova, SN 2003dh (Price et al. 2003; Hjorth et al. 2003; Stanek et al. 2003). At the same time, a class of supernovae characterized by strong explosions and possibly large asymmetries (Maeda et al. 2003) and a set of X-ray flashes with weak gamma-ray signals (e.g., Fynbo et al. 2004) were both discovered in the data.

These explosive phenomena have many similarities and are generally grouped into a large class termed “hypernovae,” with GRBs making up a subset of this class. It has been argued that non-GRB hypernovae are GRBs not directed along our line of sight or GRB-like jet explosions in which the jet is no longer relativistic when, and if, it breaks out of the star (e.g., MacFadyen et al. 2001; Fynbo et al. 2004; Zhang et al. 2004). The collapsar model (Woosley 1993; MacFadyen & Woosley 1999) is gradually becoming the favored engine behind all types of hypernova explosions.

The collapsar model cannot explain all supernova observations (Fryer et al. 1999), and there is growing observational evidence showing that these explosions are rare. Radio observations suggest that at most 5% of all Type Ib/Ic supernovae can be produced in GRBs (Berger et al. 2003). Likewise, optical observations (correcting for observational biases) of hypernovae suggest that this fraction is less than 1% (Podsiadlowski et al. 2004). Because the event rate is so low, the progenitor evolution can be much more exotic. Here we focus on progenitors for the collapsar engine alone.

The collapsar model is part of a class of models invoking accretion disks around black holes (Popham et al. 1999; Fryer et al. 1999). In the collapsar mechanism, the black hole is formed when the collapse of a massive star fails to produce a strong supernova explosion, leading to the ultimate collapse into a black hole. If the stellar material falling back and accreting onto the black hole has sufficient angular momentum, it can hang up, forming a disk. This disk, by neutrino annihilation or magnetic fields, is thought to produce the jet that finally results in a GRB or a hypernova that we observe (Popham et al. 1999; MacFadyen & Woosley 1999). For such a mechanism to work, the star must satisfy three criteria:

1. The star must collapse to a black hole. This can occur in stars that initially produce weak or no explosions.
2. The star must have sufficient angular momentum to form a disk around that black hole. The ideal range of angular momentum, $j$, in the core lies in the range $10^{46}$ cm$^2$ s$^{-1} < j < 10^{48}$ cm$^2$ s$^{-1}$.
3. The star must lose its hydrogen envelope. This criterion is necessary for the jet to remain relativistic (Zhang et al. 2004).

Some hypernovae may not need to satisfy this criterion.

In principle, massive single stars can satisfy these criteria. In the absence of winds, massive stars above $\sim 18$–25 $M_\odot$ are all believed to collapse to form black holes (Fryer 1999). With the inclusion of mass loss from winds, binary interactions, or both, many massive stars will still collapse to form black holes (Fryer et al. 2002; Heger et al. 2003). A sizable fraction of single stars, easily enough to produce the rates required to form hypernovae and GRBs, will collapse after losing their entire hydrogen envelope. If single stars are the dominant GRB progenitor, the GRB rate should decrease dramatically at high redshift, where winds do not eject the hydrogen envelope as effectively. In general, single stars that do lose their hydrogen envelope also lose a lot of their angular momentum, so it is not clear that single stars can match all three criteria.

To solve this angular momentum deficiency, in particular caused by the angular momentum loss from stellar winds, Fryer et al. (1999) proposed that the cores of massive stars in binaries would merge in a common-envelope phase, leaving behind a merged core and ejecting much of the hydrogen envelope...
without slowing down the rotation of the core. But what kind of binary scenario will cause the merged core to rotate rapidly? Figure 1 shows two evolutionary paths of binaries that lead to a merged core. In the first path (I), the primary star engulfs its companion and the two stars merge while the companion is still on the main sequence. This scenario is akin to the leading scenario for the progenitor of supernova 1987A (Podsiadlowski 1992), which can spin up the outer part of the core. Podsiadlowski (1992) argued that SN 1987A formed according to such a scenario. System II involves two stars of nearly identical mass. In the first common-envelope phase, the system tightens but does not merge. However, the similar masses of the two stars mean that the less massive star evolves off the main sequence before the more massive star collapses, leading to a second common-envelope phase and the merger of the two helium cores. Fryer et al. (1999) proposed this scenario as a formation scenario for collapsars.

Fryer et al. (1999) termed these mergers the He merger formation scenario (merger of two helium cores) for collapsars, and it is these objects that we study in this paper.

How do these objects fit into the grand scheme of binary populations? Figure 2 shows a chart of the fates of massive stars. X-ray binaries are formed in systems where the two stars do not merge. The progenitor of SN 1987A may have formed from a binary of a massive star and a low-mass companion that merged and retained much of its hydrogen envelope. Although it may seem unlikely that many binaries consisting of two stars of nearly the same mass exist, these binaries may be the primary scenario for forming double neutron star systems (Brown 1995; Fryer et al. 1999; Belczynski et al. 2002). Such incidences may be rare, but they easily can form the observed hypernova
population (Belczynski et al. 2002 found that this rate could exceed 10 mergers per Myr).

In this paper, we present the first in a series of simulations studying the actual merger of helium cores to determine whether such a merger phase can produce a collapsar and ultimately a hypernova or GRB. In §2, we describe the combination of codes used to model the merger and stellar evolution of these binary systems. The results of these calculations are given in §3, the fate of the merged cores is discussed in §4, and their implications for GRBs are given in §5.

2. COMPUTATIONS

Determining whether binary mergers (of the He-He merger class) play a role in collapsars requires a range of physics and numerical techniques including implicit hydro codes capable of modeling the evolution of a star through its entire life and simulations following the multidimensional effects of the merger itself. As such, this study, by necessity, is a multistep process:

1. Evolve each component star of the binary system from birth to the point that the common-envelope phase, and hence the merger, begins (e.g., after the stars have moved off the main sequence). This provides the structure of the stars for the next step.

2. Model the actual merger process as the two stars evolve through a common envelope to determine the thermodynamic and composition structure and angular momentum distribution of the merged core for the next step.

3. Evolve the merged star through the rest of its life to the collapse of its iron core. These simulations will produce the detailed structure and angular momentum profiles with which we can compare these binary collapsar progenitors with their single-star counterparts.

Steps 1 and 3 require full stellar evolution codes, and for these steps we use a modified version of the stellar evolution code KEPLER (Weaver et al. 1978; Heger et al. 2000; Woosley et al. 2002). The actual merger process (step 2) requires multidimensional hydrodynamic calculations, and for this step we use the three-dimensional smooth particle hydrodynamics code SNSPH (Fryer & Warren 2002; Fryer et al. 2005). Below we discuss the details of each of these steps individually, including a discussion describing our technique to map each preceding step with the next.

2.1. Initial Star Evolution

In this first paper, we focus on two different helium cores: 8 and 16 $M\odot$ helium stars at the onset of central helium burning.
It is likely that the more massive star has evolved beyond a pure helium core. Test calculations of the more evolved cores find that nuclear burning during the merger can be important. We will delay merger calculations of evolved cores until we have better tested the network in our SNSPH code (Paper II).

The stars are evolved to this state as single stars using the stellar evolution code KEPLER (Weaver et al. 1978; Woosley et al. 2002). We follow this single-star evolution until the onset of mass transfer, before helium ignition for our pure helium cores and at carbon ignition for our compact star. These stellar models are the input for our multidimensional merger calculations.

2.2. The Merger Process

To study the merger of these stars, we must map these stars into three-dimensional binary systems at the onset of mass transfer. We have three different merged systems: 8+8, 16+16, and 8+16 \( M_\odot \) binaries. Because both stars have to evolve nearly at the same time, the equal-massed systems are the most likely systems for the He merger GRB scenario that we are considering here. If the secondary star gains considerable mass from the primary during a first mass transfer phase (prior to or instead of the common envelope pictured in Fig. 1), the secondary helium core could actually be more massive than the primary helium core. The merger of an 8+16 \( M_\odot \) system represents an extreme case of this scenario. We map the stars into shells of smooth particle hydrodynamics (SPH) particles. For this multidimensional evolution, we use a simplified version of the parallel SNSPH code (Fryer & Warren 2002; Fryer et al. 2005). This simplified code uses a polytropic equation of state (assuming ideal gas: \( \gamma = 5/3 \)) and neglects nuclear burning. Because the merger process is so rapid (a few orbit cycles) and the particle temperatures do not increase significantly during the merger, our assumption that nuclear burning is unimportant holds. Both our mapping and our simplified equation of state lead to initial oscillations in the star. We first model these stars as single systems, adiabatically damping the oscillations until the star is stable.

After the stars have stabilized, we map them into a binary system. To test our angular momentum conservation and stability, we have run these stars for over 10 orbits in systems roughly 2–3 times beyond their Roche overflow separation. The total angular momentum was conserved to better than 1 part per million at the end of this simulation, and the stars remained stable with no further oscillations (see Fryer et al. 2005 for details).

For our actual merger calculations, we first assume that we can ignore the hydrogen envelope aside from its viscous forces that drive the merger. The friction caused by the hydrogen envelope is driving these two cores together. Our initial binary is set with the two cores just beyond their Roche overflow separations but with slightly decreased angular momenta (corresponding to the additional angular momentum that will be lost to friction with the hydrogen envelope). These angular momenta are given in Table 1. In this manner, we can mimic the effects of the hydrogen common envelope while concentrating our resolution on the helium cores themselves. We assume that much of the hydrogen envelope has been ejected in the hydrogen common-envelope phase, and the rest is ejected during the core merger or because of winds during subsequent evolution without affecting the structure of the core. Given the low binding energy of the hydrogen envelope with respect to the core, this assumption is valid.3

Within a few orbit timescales, the cores merge (Figs. 3 and 4). Figure 3 shows density isosurfaces of the merger of two 16 \( M_\odot \) helium stars 1.1 \( \times 10^4 \) and 3.3 \( \times 10^4 \) s after the start of the simulation. Note that as the cores merge, an accretion disk is ejected along the orbital plane. This disk will sweep up any remaining hydrogen envelope and continue to expand as the star evolves. Indeed, as the star evolves, it will lose mass in a wind, and the accretion disk will slowly accelerate throughout the last phase of the star’s life. Note also that most of the mass ejected in this merger flows out in the orbital plane, not along the orbital axis (and hence rotation axis) where the collapsar jet is likely to lie.

2.3. Final Evolution

Mapping the multidimensional simulations back into one dimension proved much more difficult. In the simplest mapping conserving mass, energy, and angular momentum, we choose a radial grid and sum the relevant quantities for all the particles in each radial zone. This mapping of a multidimensional simulation into one-dimensional code with different equations of state

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3 The main effect of any residual hydrogen envelope is to reduce the total mass lost due to winds. We mimic this effect by altering the mass loss in the subsequent evolution of the star.
conserves energy but not pressure gradients, however. Not surprisingly, the new one-dimensional star was not in equilibrium. We adjusted the temperature such that for the given density structure, which we preserved, a hydrostatic model resulted. We then simulated the remaining evolution until the onset of core collapse using the KEPLER code including angular momentum transport and rotationally induced mixing (Heger et al. 2000).

After the mapping step the star relaxes to thermal equilibrium on a Kelvin-Helmholtz timescale. At this point, another difficulty of the mapping became apparent: the outer layers of the relaxed model were vastly super-Keplerian when contracting to a nonrotating (not considering centrifugal forces) thermal equilibrium density structure. We tested different techniques to remove this unphysical situation. The three most prominent are (1) removing the entire super-Keplerian outer layer after the stars have reached thermal equilibrium (removing the material at an earlier stage of higher density could have caused excessive mass loss); (2) rotationally induced enhancement of the mass-loss rate. In particular, as long as the star exceeds the “Omega limit” (Langer 1998), high mass-loss rates could occur, formally diverging in Langer’s prescription, but here we limited the mass loss to 100 times the normal nonrotational mass-loss rate. This ensures that the outer super-Keplerian layers are lost on a timescale short compared to the evolutionary timescale but at the same time allows the star to adjust its structure to the mass reduction; and (3) removing super-Keplerian angular momentum in the outer layers without removing mass. The physical motivation for this mode of angular momentum loss is the possibility that an excretion disk could form around that star and

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**Fig. 3.—**Density contours at two different times of the merger of two $16 M_\odot$ stars. The contours correspond to densities of (from inner to outer contour) $8 \times 10^{-2}$, $10^{-3}$, and $10^{-5} \text{g cm}^{-3}$. For the mergers of identical-mass stars, the matter is ejected in an axisymmetric excretion disk. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 4.—**Density contours at two different times of the merger of an $8 M_\odot$ star with a $16 M_\odot$ star. The contours correspond to densities of (from inner to outer contour) $8 \times 10^{-2}$, $10^{-3}$, and $10^{-5} \text{g cm}^{-3}$. The merger of stars with different masses leads to a much less symmetric mass ejection than that of equal-mass stars (Fig. 3). [See the electronic edition of the Journal for a color version of this figure.]
transport angular momentum away while removing only very little mass. (The general idea behind disks, though accretion disks in most pictures studied, is that they transport mass in while transporting angular momentum outward.) In this paper, we focus on the results using assumption 1 (series a), assumption 2 (series b), and assumption 3 without any mass loss (series c; see Table 1).

Our different techniques of treating the super-Keplerian outer layers after the remapping produce different stellar structures at core collapse because of different amounts of mass loss and different rotationally induced mixing. These differences reflect part of the errors in these calculations, and we review the results from both in our analysis (Table 1). In addition, the mass loss from winds is uncertain. For our fast rotating merged systems, this mass loss is even less known. The effects of rotation on mass loss are just now being studied. In addition, we have assumed that the hydrogen envelope is ejected during the merger. However, this assumption may not be true. The existence of a hydrogen envelope will not affect the hydrodynamic merger calculations, but this hydrogen envelope must be blown off before the He core will lose mass, effectively delaying the Wolf-Rayet phase. Hence, we have also run some of our stars assuming no mass loss from the system after the binary merger (series c; see Table 1). Such a simulation mimics what we might expect if the hydrogen envelope is not entirely ejected during the merger process.

3. SIMULATION RESULTS

From Figures 3 and 4, we see that much of the initial mass and angular momentum is lost in the ejecta from the merger. Even so, the merged cores still retain 1–2 orders of magnitude more angular momentum than necessary to form an accretion disk around the nascent black hole. Figure 5 shows the equatorial angular momentum profile of all our models, both right after the merger and at collapse (after its final evolution). Note that most cores lose 99% of their angular momentum in the evolution after the merger. Without mass loss, the angular momentum is a factor of 3–10 times greater. This is because it is the mass loss from winds that carries away much of the angular momentum.

Also plotted on Figure 5 is the angular momentum necessary for the infalling material to hang up at the Schwarzschild radius in a centrifugally supported disk \( j = \frac{2GM_{\text{sc}}}{c^2} \), where \( r_{\text{sc}} \) is the gravitational constant, \( M \), the enclosed mass, and \( c \), the speed of light. If the angular momentum of the star roughly exceeds this value, a disk will form during collapse.\(^4\) The mass position where this occurs gives us the rough mass of the black hole at disk formation. We see that although some shells of material below \( 3 M_{\odot} \) have sufficient angular momentum to hang up in a disk, it is not until beyond \( 3 M_{\odot} \) (\( 4 M_{\odot} \) for the he1616 and he816 models) that the infalling material will consistently hang up in a disk of material for our models with mass loss. Hence, for most of our systems, we expect black hole masses for the collapsar engine above \( 3 M_{\odot} \).

To determine the true fate of the star (e.g., whether it forms a black hole or neutron star; if, and when, a collapsar jet is launched; etc.), we must also study its density and entropy profile. Figure 6 shows the entropy versus enclosed mass for all our models. It is the entropy in the core that determines the strength of the bounce when the core collapses down to a proto-neutron star. In general, the entropy of the series c models (no mass loss) is

\(^4\) Note that if the black hole has angular momentum, this minimum angular momentum value will decrease, to as little as \( 1/\sqrt{6} \) for a maximally rotating black hole. On the other hand, for any engine to work, the disk must form beyond the innermost stable circular orbit. How large a disk depends on the still uncertain collapsar engine.

![Fig. 5.—Mean angular momenta vs. mass for all our models just after the merger and at collapse. The thick solid line at the top of the graph is the angular momentum just after merger. Dotted lines correspond to a series models, dashed lines correspond to b series models, and dot-dashed lines correspond to c series models. We have also plotted the angular momentum for material at the innermost stable circular orbit for a nonrotating black hole vs. mass (thin solid line). Although the criterion for the formation of a disk that can drive an explosion is uncertain, it is likely that the angular momentum must consistently exceed this value. For most of our models, this is above 3–4 \( M_{\odot} \). [See the electronic edition of the Journal for a color version of this figure.]
higher in the inner 1 \( M_\odot \) core and lower just beyond that core, but these differences are neither absolute nor very strong. Figure 7 shows the density profiles for the same models. It is more difficult for those compact stars where the density remains high to masses beyond 2 \( M_\odot \) (namely, the models with no mass loss; series c) to explode, and they will more likely collapse to form black holes. We discuss this in more detail in § 4.

Last, we show the nuclear abundances at collapse of four of our models that give the full range of possible composition structures for these merged cores (Fig. 8). The smallest iron core (\( \sim 1.8 \) \( M_\odot \)) is produced by the merger of the two smallest stars (He88), but note that the iron cores (and silicon layers) for the He816a and He1616a models are nearly identical (\( \sim 2 \) \( M_\odot \)). This is because there is so much mass loss in the He1616a model that its core reflects that of a much smaller star. With mass loss turned off (He1616c), the iron core for the 16+16 \( M_\odot \) models is even larger (\( \sim 2 \) \( M_\odot \)) and the C-free (oxygen burning) layer extends to 6 \( M_\odot \) (compared to \( \sim 1.8 \) \( M_\odot \) for the He88a model and \( \sim 2.5 \) \( M_\odot \) for the He816a and He1616a models). This large silicon shell will ultimately play a major role in the fate of these stars.

### 4. THE FATE OF MERGED CORES

From the results of our simulations, we can now estimate (1) whether the collapse of such stars will produce a neutron star or black hole, (2) assuming a black hole is formed, if and when an accretion disk will form, and (3) the delay between collapse and jet formation. As we go through each of these steps, we study an increasingly select set of merged systems, ultimately determining the ideal set of collapsar candidates. We can then use the conditions required to make these candidates as a constraint on the population of GRB progenitors (§ 5.4).

The success or failure of core-collapse supernovae remains an unsolved problem in astrophysics (Herant et al. 1994; Burrows et al. 1995; Janka & Müller 1996; Mezzacappa et al. 1998; Fryer 1999; Buras et al. 2003), and core-collapse theorists have not yet identified all of the factors that determine the fate of a progenitor star. However, Fryer (1999) has found that the density profile is a good indicator of whether an explosion can occur. He argued that the sharp drop in density for the collapsed core of stars between 8 and 20 \( M_\odot \) is what allows the convective region above the proto–neutron star to expand and drive a supernova explosion. Fryer (1999) used the accretion rates on the convective core as a function of time after core bounce as a diagnostic of the fate of massive stars. This accretion exerts a ram pressure that must be overcome to drive an explosion. Low accretion rates mean a weaker ram pressure, which makes an explosion easier. The corresponding accretion rates for our merger models are plotted in Figure 9. The rates for the 15 and 25 \( M_\odot \) stars are plotted for comparison.

Many of the merger models with mass loss in this paper have accretion rates very similar to that of the 15 \( M_\odot \) star. In Fryer (1999), the 15 \( M_\odot \) exploded quickly (strong explosion, neutron...
star compact remnant). Observational evidence also suggests that 15 $M_\odot$ stars do produce strong supernova explosions and neutron star remnants. It is likely that merger models that have accretion profiles similar to the 15 $M_\odot$ star (He88a, He88b, He1616a, and He1616b) also produce strong explosions with neutron star remnants. Fryer (1999) found that the 25 $M_\odot$ star took longer to explode, producing a weak explosion and a black hole forming from fallback. The remaining models are much more similar to the 25 $M_\odot$ star, and it is likely that these models form black holes either directly (collapsar Type I) or through fallback (collapsar Type II).

Our merger models, by Ansatz, satisfy criterion 3 (loss of hydrogen envelope; § 1) of GRB progenitors. In the last paragraph, we found that He816a, He1616a, and c series all seem to satisfy criterion 1 (collapse to black hole). The final criterion that must be satisfied is the angular momentum constraint: the infalling material must have enough angular momentum to form a disk around the black hole. Figure 10 compares the angular momenta from the black hole–forming mergers with massive single stars. From Figure 5, we see that there is sufficient angular momentum to form a disk in all our black hole–forming models. Models he1616a and he1616b do not have dramatically more angular momentum than massive single stars. Those models without mass loss (c series), however, collapse with angular momenta 3–10 times higher than single-star models.

Recall that these zero mass-loss models mimic the situation in which a hydrogen envelope persists around the helium core after the merger or those evolved systems that have little mass loss before collapse. It is likely that this hydrogen will be removed prior to the collapse of the core. However, it could delay the Wolf-Rayet stage long enough to minimize the effects of mass loss.

Another way to reduce the postmerger mass loss is to assume that the primary system has evolved. If the core has already undergone some helium burning, the time between merger and collapse will be shorter. This will both reduce the mass loss and hopefully reduce the amount of angular momentum lost through viscous forces. We expect such systems to rotate faster than those of our current study.

The angular momentum in these black hole–forming stars is so high that the black hole formed in these collapses is at close to maximal rotation. This formation process begins with the collapse of the core to a rapidly spinning proto–neutron star. The fast rotating core (Fig. 5) collapses to a proto–neutron star spinning nearly at breakup. This support leads to a greater maximum neutron star mass. However, because the angular momentum increases with radius, the increase in the maximum mass will not be much more than the 20% expected for a uniform rotator (Cook et al. 1994; Morrison et al. 2004). We expect the black hole to form from a roughly 3 $M_\odot$ neutron star with enough angular momentum to produce a maximally rotating black

Fig. 7.—Same as Fig. 6, but for density vs. mass at collapse. As we could surmise from the entropy plot (Fig. 6), beyond ~1 $M_\odot$, the density is higher for the larger cores in the series c models.
hole. Such high angular momentum will aid both the magnetic field and neutrino annihilation engines driving collapsar jets. For magnetically driven collapsars, the launch of the jet can occur as soon as an accretion disk is formed. For example, Katz (1997) argues that it takes only a few differential revolutions of the disk to build up the magnetic field strength necessary to produce a jet. With the large amount of angular momentum in the black hole and the disk, the magnetically driven jet model has a large reservoir of rotational energy to drive an explosion. In this scenario, the delay between the GRB jet and the initial neutrino/gravitational wave signal can be very short (limited to the time it takes for the proto-neutron star to collapse to a black hole, < 1 s).

Neutrino annihilation is a different matter. The efficiency of energy deposition via neutrino annihilation is very low. Hence, neutrino annihilation will not drive a jet until sufficient accretion along the axis of rotation has occurred to clear out a funnel.

Fig. 8.—Abundance fractions vs. mass for four merged cores just prior to collapse. The smallest iron core (∼1.8 $M_\odot$) is produced by the merger of the two smallest stars (He88). However, the trend of smaller cores with smaller merged objects does not seem to follow with our other models. Mass loss causes the iron cores (and silicon layers) for the He816a and He1616a models to be nearly identical (∼2 $M_\odot$). The largest iron core arises from the merger of two 16 $M_\odot$ stars without mass loss (∼2 $M_\odot$). Even more important for black hole formation is the size of the silicon/sulfur layer. This layer extends to 6 $M_\odot$ for the He1616c model (compared to ∼1.8 $M_\odot$ for the He88a model and ∼2.5 $M_\odot$ for the He816a and He1616a models). [See the electronic edition of the Journal for a color version of this figure.]
As the axis clears, the energy deposition will be sufficient to drive an explosion (Fryer & Mészáros 2003). Fryer & Mészáros (2003) showed that the black hole mass at, and the delay from collapse to black hole formation can be solved semianalytically for a given stellar density profile. Figure 11 shows the density profiles for our merged cores in comparison with single-star models. From these densities, we derive the accretion rate along the rotation axis as a function of time (Fig. 12). When this rate falls below the critical rates derived by Fryer & Mészáros (2003), the jet is launched. Note that these estimates all predict black hole masses above \( \frac{24}{10} \frac{M}{L} \) and delay times above 50 s (Table 1). It is unlikely that the neutrino-driven mechanism will work for these stars. The neutrino-driven mechanism may not work for any stars that will ultimately form black holes.

5. IMPLICATIONS FOR NEUTRON STAR, BLACK HOLE, AND GRB POPULATIONS

Close binaries are observed. Systems that do not merge produce X-ray binaries and double neutron star binaries such as the Hulse-Taylor pulsar system. Those that do merge may produce equally interesting objects, from SN 1987A to GRBs. This paper focuses on the evolution of a class of progenitors for GRBs known as He star/He star mergers (Fryer et al. 1999). We find that under conditions with little mass loss, He star/He star mergers systems have 3–10 times more angular momentum than single-star collapsar progenitors. Nevertheless, if the mass loss is high, these merged systems form neutron stars, not black holes. Unfortunately, the true fate of any binary is extremely sensitive to mass loss, and our capability to predict this is, in turn, limited by our knowledge, or lack thereof, of wind mass loss in rotating stars, as well as the amount of hydrogen left in these merged systems, which depends on the specifics of the merger event itself. Even with these uncertainties, we can already use our current results to predict the neutron stars, black holes, and GRBs formed by these binaries. Before we do, let us review once more the mass-loss uncertainties.

5.1. Mass-Loss Uncertainties

The subject of mass loss from winds has long been in dispute between the stellar and X-ray binary communities. The stellar community has long argued that both observations of stars and the number of Wolf-Rayet stars require high wind mass-loss rates. The smooth mass-loss prescriptions produced by stellar
theorists generally cause most massive stars to lose most of their mass prior to collapse. Solar metallicity stars in binaries that lose their mass during case B mass transfer (during the expansion off the main sequence) have no chance of forming black holes without artificially lowering the currently predicted mass-loss rates (see Fryer et al. 2002 for a review). And yet case B mass-transfer binaries dominate the production of X-ray binaries, and X-ray binaries are observed in considerable numbers in the Galactic disk.

The situation is such that either (1) mass-loss rates are lower (which stellar theorists argue cannot be the case because then they cannot make Wolf-Rayet stars) or (2) binary population synthesis theorists have not found the correct path for making X-ray binaries. Solving this problem is essential to understanding the progenitors of GRBs and requires a better physical understanding of mass loss (which may include pulsational studies; J. Guzik 2004, private communication); we believe lower mass-loss rates, at least for some stars, will be the ultimate solution. This is, in part, because of the false assumption that the numbers of Wolf-Rayet stars require high mass-loss rates. Recall (Fig. 2) that binaries can also make Wolf-Rayet stars. Indeed, Podsiadlowski et al. (1992) have shown that binaries can dominate the Wolf-Rayet rate. On the other hand, Meynet & Maeder (2003) argue that the fraction of Wolf-Rayet stars as a function of metallicity is better fitted by single-star models than binary systems, implying that single stars are the dominant Wolf-Rayet progenitor. Thus, the progenitors of Wolf-Rayet stars remain a matter of contention.

There are additional uncertainties in binary merger calculations. In this paper, it was assumed that the hydrogen envelope provided the last bit of friction to merge the binaries but was otherwise ignored. It could be that even after the merger, some hydrogen remained at the surface of the star. Although this does not affect the hydrodynamical merger process significantly, it will change the mass loss dramatically, as the star will not enter the Wolf-Rayet phase until after this hydrogen is shed. Unfortunately, the amount of hydrogen remaining will depend on the binary characteristics. It is likely that our studies, in the near future, will be limited to qualitative trends.
about the compact systems and explosions resulting from these mergers.

5.2. Neutron Star Remnants

Those systems with small helium cores (either through smaller mergers not studied in this paper or those that lose considerable mass through winds) will form rapidly rotating neutron stars, with rotational velocities at least as large as the fastest rotating single stars. These stars will collapse to form proto-neutron stars surrounded by a disk (thermally and centrifugally supported) that is likely to dissipate the angular momentum before the material contracts and gains considerable kinetic energy (Fryer & Heger 2000; Fryer & Warren 2004). If large magnetic fields are produced in these proto-neutron stars, this angular momentum dissipation will occur even earlier. With our current understanding of the disk evolution, these objects will not produce GRBs (which require periods below 1 ms), but they will form fast-spinning pulsars.

Because the mass loss increases with metallicity, we should see more neutron star systems with increasing mass. Since the neutron star population will be dominated by smaller helium cores, this increase may easily be hidden. The black hole formation rate, on the other hand, will change dramatically.

5.3. Black Hole Remnants

Those mergers that do not lose considerable mass will collapse to form black holes. Because of the low mass loss, these stars have 3–10 times more angular momentum just prior to collapse. The black holes will be born, preferentially at low metallicities (depending on our understanding of mass loss) with spin rates that are higher than those produced in single stars. The high angular momentum in the infalling star will form a disk around the black hole, possibly forming a GRB jet.

5.4. GRBs

The collapsar engine for GRBs has three possible progenitors (Fryer et al. 1999): single stars, the merger of a compact remnant and its binary companion (He merger), and the merger of two helium cores (He star/He star merger) studied in this paper. Single-star progenitors suffer from having insufficient angular momentum. As we have seen in this paper, this angular momentum problem may be somewhat alleviated with He star/He star mergers. The He merger model might have the opposite problem: too much angular momentum (see Zhang & Fryer 2001; Di Matteo et al. 2002).

All three of these progenitors may be contributors to the GRB population, but they have very different redshift distributions. Both the helium merger and He star/He star merger scenarios can occur at large redshifts (low metallicities). The single-star progenitors decrease significantly with lower metallicity. If they are the sole contributor, there should be very few long-duration bursts at high redshifts and none from Population III stars even though the initial mass function might be skewed toward massive stars at these high redshifts. This sharp decrease is because single stars cannot blow off their hydrogen envelopes without metals. It is harder to determine the redshift evolution of binary systems without detailed population synthesis calculations. Lower mass loss and the skewed initial mass function increase the number of close binaries that collapse to black holes. However, low- and zero-metallicity stars tend to expand less in their giant phases, leading to fewer mass transfer phases. Keeping in mind these uncertainties, we still predict that the fraction of stars that form GRBs under binary scenarios increases with redshift. The redshift distribution of GRBs will allow us to easily distinguish between GRB progenitors.

If He star/He star mergers are the dominant progenitor of GRBs, we can make a few further predictions beyond the increase in GRB formation rate with redshift. The progenitors are more massive and have more angular momentum with increasing redshift. Hence, there should be a steady evolution of the GRB energy with increasing redshift. Although it is certainly plausible for these more massive, faster rotating stars to make stronger bursts at higher redshifts, without a full understanding of the GRB engine, no reliable predictions can be made.

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REFERENCES

Belczynski, K., Bulik, T., & Kalogera, V. 2002, ApJ, 571, L147
Berger, E., Kulkarni, S. R., Frail, D. A., & Soderberg, A. M. 2003, ApJ, 599, 408
Brown, G. E. 1995, ApJ, 440, 270
Buras, R., Rampp, M., Janka, H.-Th., & Kifonidis, K. 2003, Phys. Rev. Lett., 90, 241101
Burrows, A., Hayes, J., & Fryxell, B. A. 1995, ApJ, 450, 830
Cook, G. B., Shapiro, S. L., & Teukolsky, S. A. 1994, ApJ, 422, 227
Di Matteo, T., Perna, R., & Narayan, R. 2002, ApJ, 579, 706
Fryer, C. L. 1999, ApJ, 522, 413
Fryer, C. L., Burrows, A., & Benz, W. 1998, ApJ, 496, 333
Fryer, C. L., & Heger, A. 2000, ApJ, 541, 1033
Fryer, C. L., Heger, A., Langer, N., & Wellstein, S. 2002, ApJ, 578, 335
Fryer, C. L., & Meszaros, P. 2003, ApJ, 588, L25
Fryer, C. L., Rockefeller, G., & Warren, M. S. 2005, ApJ, submitted
Fryer, C. L., & Warren, M. S. 2002, ApJ, 574, L65
—. 2004, ApJ, 601, 391
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJ, 526, 152
Fynbo, J. P. U., et al. 2004, ApJ, 609, 962
Heger, A., Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 2003, ApJ, 591, 288
Heger, A., Langer, N., & Woosley, S. E. 2000, ApJ, 528, 368
Herant, M., Benz, W., Hix, W. R., Fryer, C. L., & Colgate, S. A. 1994, ApJ, 435, 339
Hjorth, J., et al. 2003, Nature, 423, 847
Ivanova, N., Podsialowski, Ph., & Spruit, H. 2002, MNRAS, 334, 819
Janka, H.-Th., & Müller, E. 1996, A&A, 306, 167
Katz, J. 1997, ApJ, 490, 633
Langer, N. 1998, A&A, 329, 551
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
MacFadyen, A. I., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 410
Maeda, K., Mazzali, P. A., Deng, J., Nomoto, K., Yoshii, Y., Totma, H., & Kobayashi, Y. 2003, ApJ, 593, 911
Meynet, G., & Maeder, A. 2003, A&A, 404, 975
Mezzacappa, A., Calder, A. C., Blondin, S. W., Blondin, J. M., Guidry, M. W., Strayer, M. R., & Umar, A. S. 1998, ApJ, 495, 911
Morrison, I. A., Baumgarte, T. W., & Shapiro, S. L. 2004, ApJ, 610, 941
Podsiadlowski, P. 1992, PASP, 104, 717
Podsiadlowski, P., Joss, P. C., & Hsu, J. J. L. 1992, ApJ, 391, 246
Podsiadlowski, P., Mazzali, P. A., Nomoto, K., Lazzati, D., & Cappellaro, E. 2004, ApJ, 607, L17
Popham, R., Woosley, S. E., & Fryer, C. L. 1999, ApJ, 518, 356
Price, P. A., et al. 2003, Nature, 425, 844
Stanek, E. Z., et al. 2003, ApJ, 591, L17
Weaver, T. A., Zimmerman, G. B., & Woosley, S. E. 1978, ApJ, 225, 1021
Woosley, S. E. 1993, ApJ, 405, 273
Woosley, S. E., Heger, A., & Weaver, T. A. 2002, Rev. Mod. Phys., 74, 1015
Zhang, W., & Fryer, C. L. 2001, ApJ, 550, 357
Zhang, W., Woosley, S. E., & Heger, A. 2004, ApJ, 608, 365