LONG GAMMA-RAY TRANSIENTS FROM COLLAPSARS

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ABSTRACT

In the collapsar model for common gamma-ray bursts (GRBs), the formation of a centrifugally supported disk occurs during the first $\sim10$ s following the collapse of the iron core in a massive star. This only occurs in a small fraction of massive stellar deaths, however, and requires unusual conditions. A much more frequent occurrence could be the death of a star that makes a black hole and a weak or absent outgoing shock, but in a progenitor that only has enough angular momentum in its outermost layers to make a disk. We consider several cases where this is likely to occur—blue supergiants with low mass-loss rates, tidally interacting binaries involving either helium stars or giant stars, and the collapse to a black hole of very massive pair-instability supernovae. These events happen in common the accretion of a solar mass or so of material through a disk over a period much longer than the duration of a common GRB. A broad range of powers is possible, $10^{47}$–$10^{50}$ erg s$^{-1}$, and this brightness could be enhanced by beaming. Such events were probably more frequent in the early universe where mass-loss rates were lower. Indeed, this could be one of the most common forms of gamma-ray transients in the universe and could be used to study first generation stars. Several events could be active in the sky at any one time. Recent examples of this sort of event may have been the Swift transients Sw-1644+57, Sw-2058+0516, and GRB 101225A.

Key words: dark ages, reionization, first stars – gamma rays: stars – stars: massive – supernovae: general

1. INTRODUCTION

The collapsar model (Woosley 1993) was originally proposed as an explanation for common, “long-soft” gamma-ray bursts (GRBs) with durations near 20 s. This is a typical timescale for the gravitational collapse of the carbon–oxygen core of a massive star and the congruence of these timescales was an argument in favor of the model. It is well known, however, that forming a disk so quickly requires an unusually large amount of angular momentum to be stored in the core up to the point when the star dies (e.g., Woosley & Heger 2006). This is presumably one reason why GRBs are rare compared with supernovae.

Black holes are expected to form in a significant fraction of massive star deaths (e.g., O’Connor & Ott 2011) and it seems possible that, in at least some of these, the black hole will form without generating an outgoing shock. What observable signal would accompany such an event? Would they all be “un-novae” (Kochanek et al. 2008), stars that simply suddenly disappear from view? Or will some sort of transient display announce the birth of any black hole? Here we explore the possibility that these black hole systems form an accretion disk, but only after almost all of the star has fallen into the hole. Torques in differentially rotating stars tend to concentrate angular momentum in the star’s outer layers as their cores contract. The stellar surface will also develop a large angular momentum in a tidally locked system. On the other hand, stellar mass loss preferentially removes these same layers, so, just as in the usual collapsar model, reducing mass loss, e.g., by reducing the metallicity, favors the retention of high angular momentum at the stellar surface.

Because the outer layers of the star take longer to fall in—months to years in the case of a red supergiant—the duration of any transient produced by accretion through a disk in these cases will be much longer than for the common GRBs studied so far. They might even be confused with other forms of gamma-ray transients like those arising from supermassive black hole accretion in active galaxies (Quataert & Kasen 2011; Woosley 2012).

Here we shall consider four varieties of long-duration transients categorized by the kind of system where they occur: (1) single supergiants with metallicity less than about 0.1 $Z_\odot$ and low mass loss (Section 3.1); (2) red or blue supergiants in tidally locked, or nearly tidally locked binaries (Section 3.2); (3) pair instability induced collapse to a black hole (Section 3.3); and (4) helium stars in tidally locked binaries (Section 3.4). In each case, the duration of the transient that is produced is correlated with the radius of the pre-supernova star, hence shortest for the helium stars, while the luminosity is inversely correlated with the radius, hence faintest for the red supergiants. As with common GRBs, we are unable to predict ab initio the spectrum of these transients or the efficiency for converting black hole accretion rate into electromagnetic radiation. Presumably, as in other forms of transients powered by very rapidly accreting, rotating black holes, accretion energy, and black hole spin energy power relativistic bi-polar outflows. Poynting flux, shocks within these outflows, and shocks with the circumstellar medium make X-rays and gamma rays. It is common to take an efficiency of 1%–10% times $M c^2$ for the efficiency (e.g., McKinney 2006) thus suggesting an integrated power of $10^{42}$ erg–$10^{53}$ erg per solar mass accreted. Interestingly, these “failed supernovae” (Woosley 1993) are far more brilliant and powerful than their (modelwise) more successful cousins, ordinary supernovae.

The idea that late time accretion in supernovae that make black holes might power very long gamma-ray (or hard X-ray) transients was suggested by MacFadyen et al. (2001). The transients discussed there, referred to as “Type 2 collapsars,” were produced because of fallback in an explosion that launched a relatively weak outgoing shock in a red supergiant progenitor. Suwa & Ioka (2011) studied jet propagation and break out in similar models in the context of Population III stars and showed that the density structure of such stars allowed a jet...
to be powered for a sufficiently long time to escape the envelope of even a red supergiant star. They also estimated the efficiency for converting accretion rate to luminosity and found that very long transients would result.

Little attention was given in either of these studies, however, to the possibility that the black hole might form without any outgoing shock so that the polar regions were largely clear of matter by the time the disk formed, or to the angular momentum distribution necessary to form a disk. Here we consider a wider variety of progenitors and pay close attention to the angular momentum, especially in the outermost layers. Li (2003) also discussed the possibility of extremely long-duration X-ray transients powered by fallback and accretion through a disk. He suggested that these might look like “ultra-luminous X-ray sources” seen in nearby galaxies. These would be much longer in duration (thousands of years) and have much lower luminosity than the events considered here, but are an example of the same general idea. López-Cámara et al. (2010) too emphasized that transients, and variability in those transients, might be possible in the collapsar model, given a range of possible distributions of angular momentum in the pre-supernova star.

More relevant to this paper, Quataert & Kasen (2011) and Woosley (2012) have suggested that fallback, or a failed explosion in a red supergiant could give a long-duration gamma-ray transient that might be confused with a gamma-ray blazar. Quataert & Kasen, in particular, proposed this as an alternate interpretation of Swift transient Sw-1644+57 (Levan et al. 2011; Burrows et al. 2011). Woosley’s paper, which has been “in press” for some time, was accepted in final form prior to the discovery of Sw-1644+57. Interest has intensified as other transients similar to Sw-1644+57 were observed. Sw-2058+0516, discovered by Cenko et al. (2012), had similar properties and was also attributed to stellar disruption by a supermassive black hole. This event had an (equivalent isotropic) X-ray luminosity of about 3 × 10^{49} erg s^{-1} and lasted for months, strongly suggestive of beamed emission. The “Christmas burst,” GRB 101225A, one of the longest GRBs ever observed by Swift (Thöne et al. 2011) prior to Sw-1644+57, had a characteristic duration over 2000 s and a gamma-ray isotropic-equivalent energy release (at z = 0.33) of over 1.4 × 10^{51} erg. The host may have been a blue star-forming galaxy (Thöne et al. 2011). Interestingly, this event had a spectrum typical of an X-ray black body with a radius ∼2 × 10^{13} cm, too small for a supermassive black hole, and a temperature of ∼10^7 K. It was attributed by its discoverers to a helium star merging with a neutron star with the black body spectrum generated by the jet interacting with a recently ejected common envelope. These events demonstrate that the population of very long gamma-ray and hard X-ray transients is not necessarily small and may not be confined to an old stellar population.

A variety of other models have also been suggested for long-duration bursts. For example, a white dwarf (Fryer et al. 1999) or helium star merging with a black hole or neutron star (Fryer & Woosley 1998; Zhang & Fryer 2001). A neutron star or black hole merging with a giant star might give a Thorne–Zytkow object (Terman et al. 1995; Podsiałowski 2007) or a black hole accreting at a rapid rate (Chevalier 1993). Helium star merger with a compact object also gives a long transient of some sort (Fryer & Heger 2005). Here we consider only those transients coming from stars that are not actively merging with a companion. Because black hole formation is probably a common occurrence in massive stars, these may be the more common events.

2. THE PRODUCTION OF STELLAR MASS BLACK HOLES AND TYPE 3 COLLAPSARS

A black hole will form inside a massive star when a sufficient concentration of matter and energy accumulates to form an event horizon. The simplest possibility is that some portion of a massive star experiences an instability and falls freely, or almost freely, until it reaches such a high density that a trapped surface is formed. This rarely happens in nature though. Only in the most massive stars experiencing a pair instability (Heger & Woosley 2002) or a general relativistic instability (Fuller et al. 1986; Montero et al. 2011) can a trapped surface form before the center reaches nuclear density and bounces. That is, black hole formation in a massive star is almost always preceded by protoneutron star formation (O’Connor & Ott 2011).

For stars in the range ∼20–100 M_⊙, however, the protoneutron star that is formed experiences rapid accretion from the surrounding layers of heavy elements—silicon, oxygen, etc. If rotation, magnetic fields and neutrinos do not readily produce an outgoing shock, the hot protoneutron star grows beyond a critical mass and collapses. The accretion rate is larger for more massive helium cores (Fryer 1999), and black hole formation without an outgoing shock may be a frequent occurrence in stars with main-sequence masses over about 20 M_⊙ (O’Connor & Ott 2011; Smartt 2009). Whether all stars above about 20 M_⊙ produce black holes without outgoing shock waves is uncertain, but the possibility is not presently precluded by observations (Horiuchi et al. 2011) or theory. “Prompt” black hole formation is probably more likely in very low metallicity stars that have experienced little mass loss and thus have especially large helium cores, but it could occur for solar metallicity stars, depending upon the uncertain mass-loss rate (Smith et al. 2011) and binary interaction.

It is also possible that such a weak outgoing shock is generated that most of the star fails to explode and a black hole is made by fallback (Zhang et al. 2008). These were the systems explored by MacFadyen et al. (2001). The ones treated here differ in assuming that any outgoing shock is insufficient to eject more than a small fraction of the surface layers of the star. We shall call such events, where only the surface layers have enough rotation to form a disk and a shock so weak that these layers are not ejected “Type 3 Collapsars.” This is to distinguish them from ordinary GRBs where the disk forms promptly from material deep inside a highly differentially rotating helium core (Type 1; Woosley 1993; MacFadyen & Woosley 1999) and from systems where longer duration transients result from the delayed fallback of other material also deep inside the star (Type 2; MacFadyen et al. 2001; Heger et al. 2003).

3. EXAMPLES OF TYPE 3 COLLAPSARS

The preservation of angular momentum in the surface layers of the star can occur either because mass loss is inefficient in a single star or because of tidal interaction with a close companion. Here we consider examples of both sorts.

3.1. Massive Stars with Low Metallicity and Low Mass Loss

A paucity of metals in a star affects its evolution in several ways—reduced energy generation by the CNO cycle in the hydrogen burning shell, reduced opacity, and reduced mass loss. Of these effects, the reduction in mass loss is least well understood, but the lack of atomic lines in the atmosphere on the main sequence and of grains as a red giant seems certain to lead to some reduction. A common assumption is that the mass loss
for massive main-sequence stars depends upon some fractional power of the metallicity (Kudritzki 2002). More important and less certain is the dependence of mass lost as a red or blue supergiant on metallicity. It is thought that mass loss from cool giants is more dependent upon pulsations and grain formation (Reimers 1977; Smith et al. 2011). One might expect therefore a rapid falloff in mass loss below some value necessary for significant grain production. It has been estimated that red giant mass loss will be significantly less below 0.1 Z⊙ (Bowen & Willson 1991; Zijlstra 2004).

If stars do not lose mass then they conserve angular momentum. Since the natural course of evolution leads to the contraction and spin up of the inner star, shear instabilities and magnetic torques will concentrate an increasing amount of angular momentum in the outer regions of the star. While the inner part does spin faster due to contraction, it actually loses most of its initial angular momentum by the time it reaches central carbon burning. Heger & Woosley (2010) surveyed the evolution of non-rotating zero-metal massive stars from 10 M⊙ to 100 M⊙. In a parallel study currently underway (A. Heger & S. E. Woosley 2012, in preparation), we are surveying the evolution of rotating stars in the same mass range with metallicity 0, 10⁻³, and 10⁻¹ that of the Sun. The two stars discussed here have been extracted from that survey and are typical in the way that they accumulate large amounts of angular momentum in their outer layers before dying as supergiants. All calculations of stellar evolution presented here used the KEPLER code (Weaver et al. 1978; Woosley et al. 2002; Heger et al. 2000) and included angular momentum transport by magnetic torques (Spruit 2002). Models V24 and V36 are 24 M⊙ and 36 M⊙ main-sequence stars with metallicity 0.1% solar. Both stars rotated rigidly on the main sequence with a moderate surface equatorial speed of about 200 km s⁻¹ which is about 20% of the Keplerian value. Both pre-supernova stars had hydrogenic envelopes that were, throughout most of their mass, radiative. Model V36, however, had a low-mass surface convection zone that included 0.11 M⊙. Model V36 was consequently a yellow supergiant at death (L = 2.2 × 10³⁹ erg s⁻¹; R = 5.4 × 10¹³ cm; T_eff = 5700 K). Model V24 was a rather large blue supergiant (L = 1.1 × 10³⁹ erg s⁻¹, R = 1.0 × 10¹³ cm; T_eff = 11, 300 K).

These two stars ended their lives with cores of helium and heavy elements of 8.3 M⊙ and 15.0 M⊙, respectively, and angular momentum distributions as shown in Figure 1. While the lack of sufficient angular momentum within the helium core precludes making a disk around a black hole within that mass, there is ample rotation in the outer part of the hydrogen envelope to do so. This could be a very common occurrence. From the survey of A. Heger & S. E. Woosley (2012, in preparation), the total angular momentum of a massive star at birth that has an equatorial rotation speed of about 20% Keplerian on the main sequence is

\[ J_{\text{tot}} = I \omega \approx 2 \times 10^{52} \left( \frac{M}{M_\odot} \right)^{1.8} \text{erg s.} \]  

(1)

If the star does not lose mass, most of this angular momentum becomes concentrated, in the pre-supernova star, in a nearly rigidly rotating hydrogenic envelope with radius either \( \lesssim 10^{13} \) cm (blue supergiant) or \( \sim 10^{14} \) cm (red supergiant). Though the density declines with radius in the actual envelope, one can obtain some interesting scaling relations by assuming constant density. For a moment of inertia, \( I \approx 0.4 M R^2 \), the angular velocity at the surface, \( R = 10^{14} R_{14} \) cm, is

\[ \omega \approx 1.2 \times 10^{-10} R_{14}^{-2} \left( \frac{M}{20 M_\odot} \right)^{0.8} \text{rad s}^{-1}. \]  

(2)

The specific angular momentum of this rigidly rotating envelope is \( j = (2/3)\omega r^2 \), or about 10¹⁸ cm² s⁻¹ at the surface of a red supergiant and 10¹⁷ cm² s⁻¹ for a blue supergiant, if no mass is lost.

These can be compared with the angular momentum required to make a disk around a non-rotating black hole, \( j = 2\sqrt{3}GM/c \approx 3.1 \times 10^{17}(M_{\text{BH}}/20 M_\odot) \text{cm}^² \text{s}^{-1} \) or \( j = 2\sqrt{3}GM/c \approx 1.0 \times 10^{17}(M_{\text{BH}}/20 M_\odot) \text{cm}^² \text{s}^{-1} \) for a maximally rotating hole (Kerr parameter \( a = 1 \)). All massive stars that do not lose mass have sufficient angular momentum in their outermost layers to make a disk around any black hole formed in their collapse.

Of course, stars do lose mass and the fact that, for constant \( \omega \), \( j \propto r^2 \) means that the first mass to be lost contains most of the angular momentum. In practice, we find that a red supergiant that loses more than a few percent of its total mass before dying will probably not make a black-hole–disk system.

Figure 1. Distribution of angular momentum with respect to mass in the pre-supernova models for V24 and V36. The smooth curves show the angular momentum required to form a stable disk at the last stable orbit of a Schwarzschild black hole (lower curve) or Kerr black hole (upper curve) including the given mass. The intermediate curve that follows the Schwarzschild curve until far out in the star uses the integrated angular momentum in the model to determine the last stable orbit. Where the irregular dark line showing the actual angular momentum on the star intersects this line a disk can form. The outer 9 M⊙ of Model V24 and the outer 10 M⊙ of Model V36 will form a disk. The edge of the helium cores of the two models is apparent in the sharp inflection in the angular momentum at 8.3 M⊙ and 15.0 M⊙. Mass loss was included in the calculation, but due to the low metallicity, only 0.05 M⊙ and 0.15 M⊙ was lost in V24 and V36, respectively. Note that, if all the surface material accreted here, the black hole would rotate at nearly its maximum allowed value (i.e., the red line intersects the green one at the end).
This sensitivity to mass loss is illustrated by the evolution of a 25 $M_\odot$ model, O25, with 10% solar metallicity in a calculation that included mass loss at one-half the standard value for that metallicity. The star lost 1.17 $M_\odot$ (5%) of its mass and died as a red supergiant with a radius of 1.1 $\times$ 10$^6$ cm. The value of $f$ in its outermost layers was 2.8 $\times$ 10$^{16}$ cm$^2$ s$^{-1}$, too little to form a disk around a Schwarzschild black hole, but possibly just enough to form a disk around a mildly rotating one. The point where $j$ declined to one-half its surface value in the pre-supernova star was located 5 $R_\odot$ interior. This is borderline case. Stars with less mass loss, i.e., lower metallicity, and stars that never become red giants could make long gamma-ray transients (Table 1).

### 3.2. Supergiants in Interacting Binaries

Based upon theoretical models for single massive stars, the red supergiant progenitors of common Type IIp supernovae are not expected to have rapidly rotating envelopes. Expansion to a red giant slows the surface layers. Torques transfer the angular momentum of the more rapidly rotating inner regions outwards concentrating it in the outermost layers. For stars of sufficient metallicity, stellar winds are efficient at removing these layers and, along with them, most of the star’s angular momentum. For example, a 25 $M_\odot$ solar metallicity star rotating rigidly with an equatorial speed of 200 km s$^{-1}$ on the main sequence ends up with a 12.1 $M_\odot$ supernova progenitor if commonly used estimates for mass loss are employed (Woosley & Heger 2007). The surface rotation rate of that red supergiant ($R = 9 \times 10^3$ cm) is $2 \times 10^{-12}$ rad s$^{-1}$ and its angular momentum at the surface is $1.6 \times 10^{46}$ cm$^2$ s$^{-1}$. Nowhere in the star does any matter have enough angular momentum to form a disk around a black hole. If a black hole forms without making an outgoing shock, the envelope that is convective at any one time, however, is only $\approx 10^9$ $M_\odot$.

The circularization time $\tau_{\text{circ}}$ is (Verbunt & Phinney 1995; Phinney 1992)

$$\frac{1}{\tau_{\text{circ}}} = f \left( \frac{L}{M_{\text{env}} R^2} \right)^{1/3} \frac{M_{\text{env}}}{M} \frac{M}{M + M} \left( \frac{R}{d} \right)^8,$$

where $f$ is a number close to unity. The lifetime of a 25 $M_\odot$ main-sequence star as a red supergiant is approximately 700,000 yr, depending upon uncertain convection parameters. The mass of the envelope that is convective at any one time, however, is only about 3 $M_\odot$ and the star loses more than this in its lifetime. A more appropriate timescale might be the time the star spends losing its last 3 $M_\odot$, which is about 250,000 yr. The mass of the star when it becomes a supernova is 12.1 $M_\odot$ and we assume a companion mass of, e.g., 6 $M_\odot$. The luminosity of the star as a red supergiant is $1.0 \times 10^{39}$ erg s$^{-1}$ and its moment of inertia is approximately $4 \times 10^{46}$ g cm$^{-2}$. Equation (3) then implies that during its last 250,000 yr, stars in orbits with separations $d \lesssim 3.8 R \approx 18$ AU will circularize.

The synchronization timescale for co-rotation is somewhat different (Zahn 1977, 1989) and, in the present case, is easier to achieve

$$\frac{1}{\tau_{\text{sync}}} = 6q^2 \lambda_{\text{sync}} \left( \frac{L}{M_{\text{env}} R^2} \right)^{1/3} M_{\text{env}}^2 \frac{M}{M} \left( \frac{R}{d} \right)^6,$$

Most of the angular momentum is in the hydrogen envelope and, from the same 25 $M_\odot$ model, $M R^2 / I = 2.9$. With $q \approx 1$ and $\lambda_{\text{sync}} \approx 0.02$ (Zahn 1989),

$$\frac{1}{\tau_{\text{sync}}} \approx 0.1 \left( \frac{L}{M_{\text{env}} R^2} \right)^{1/3} \left( \frac{R}{d} \right)^6,$$

which only requires $d \lesssim 6.7 R$ for synchronization in 250,000 yr. In such a system, the period will be shorter than about 30 years ($\omega = 10^{-8}$ rad s$^{-1}$). Systems much closer will merge or experience mass exchange, so we take this to be a typical rotation period for the envelope in a detached binary system that might achieve corotation. Longer period systems will still transfer significant rotation to the envelope, however.

This is about four orders of magnitude more angular momentum in the outer envelope than in the case of the single star. Since the outer several solar masses of the pre-supernova star are convective, this rotation rate will persist to some depth. All of that mass would have sufficient angular momentum to form an accretion disk if its helium core collapsed to a black hole. Even then though, the total angular momentum of the envelope,

| Type       | Model | $M_{\text{env}}$ ($M_\odot$) | $R$ (cm) | $R_{\text{esc}}$ (s) | $M$ ($M_\odot$) | $1% M c^2$ (10$^{46}$ erg s$^{-1}$) |
|------------|-------|-------------------------------|---------|----------------------|----------------|-----------------------------------|
| BSG        | V24   | 10.0                          | (0.4–10) $\times 10^{12}$ | 20,000              | 5               | 9                                 |
|            | V36   | 10.2                          | (1–50) $\times 10^{12}$   | 60,000              | 1               | 2                                 |
| RSG-loZ    | Q25   | 0.2                           | (0.1–9) $\times 10^{13}$  | 3 $\times 10^9$     | 0.01             | 0.02                             |
| RSG-bin    | S25   | 2.8                           | (0.1–9) $\times 10^{13}$  | 3 $\times 10^5$     | 0.7              | 1                                 |
|            | Z250A | 19.6                          | (0.9–8) $\times 10^{13}$  | 3 $\times 10^8$     | 2                | 4                                 |
|            | Z250B | 20.6                          | (0.4–6) $\times 10^{13}$  | 100                 | 20               | 40                               |
| WR-bin     | 8A    | 0.18                          | (2.5–5) $\times 10^{10}$  | 100                 | 100              | 200                              |
|            | 8B    | 0.19                          | (1–5) $\times 10^{10}$    | 100                 | 100              | 200                              |
|            | 16A   | 0.01                          | (3–4) $\times 10^{10}$    | 100                 | 100              | 200                              |
|            | 16B   | 0.83                          | (2–4) $\times 10^{10}$    | 40                  | 200              | 300                              |
2.0 \times 10^{53} \text{ erg s}^{} would be a small fraction of the orbital angular momentum of the binary pair of stars. The addition of only 1\% of the angular momentum estimated here would still result in large quantities of material forming a disk, so the range of binary separations allowed is actually larger, perhaps by a factor \sim (100)^{1/6}, or about two.

Since the timescale for material to fall in from 10^{13} to 10^{14} cm is longer than any realistic viscous timescale for the disk, the accretion rate will be given by the collapse timescale of the envelope. For matter at the base of the hydrogen shell where a disk would first form, the enclosed mass is 9.3 \text{ M}_\odot and the radius about 1 \times 10^{13} cm. At the outer edge of the star the mass is 12.1 \text{ M}_\odot and the radius, 9.8 \times 10^{13} cm. The corresponding free fall times (\tau_{ff} = \left(24\pi G\rho\right)^{-1/2} = 446 (\rho/1 \text{ g cm}^{-3})^{-1/2} \text{ s}) are 2.1 \times 10^{5} \text{ s} and 5.7 \times 10^{5} \text{ s} suggesting that the event would last for months. Accreting 3 \text{ M}_\odot in 10^{6} \text{ s with 10\% efficiency for converting accreted mass to outgoing energy would give a jet power of 10^{54} \text{ erg s}^{-1}. Conversion of only 10\% of the jet power (1\% of the accreted mass energy) into gamma-rays would explain the recently discovered transient Sw-1644+57 (Levan et al. 2011; Burrows et al. 2011), especially if moderate beaming were invoked.

Though the focus here is on red supergiants because they give the longest transients; tidal locking would also occur in blue supergiants with smaller radii. The key point is that forced co-rotation with a body in Keplerian orbit gives, for a large range of orbital separations, envelope material that is rotating too fast to accrete, without hindrance, into a stellar mass black hole. Since the timescale for accretion is set by the collapse time for the outer part of the star, not the viscous times of the disk, a transient from a tidally locked blue supergiant would be similar in duration, within a factor of a few, to those studied for single blue supergiants in Section 3.1. Blue supergiants, however, will have less mass in the outer layers of the envelope and hence would have less powerful outbursts (the Appendix and Quataert & Kasen 2011).

3.3. The Pair Instability in Very High Mass Stars

Following helium burning, non-rotating helium cores with masses greater than 133 \text{ M}_\odot will collapse directly into black holes with no outgoing shock (Heger & Woosley 2002). The collapse is caused by the pair instability and, above this mass, nuclear burning is unable to reverse the implosion. Rotation, unless it is very rapid and highly differential, does not change this mass limit greatly since the instability exists in the deep interior where the ratio of centrifugal force to gravity is small.

The collapse of a rotating pair-unstable star to a black hole was followed in two dimensions by Fryer et al. (2001). First, a 300 \text{ M}_\odot main-sequence star was evolved to the point of instability in the KEPLER (1D) code. This yielded a helium core of 180 \text{ M}_\odot. The initial star was assumed to rotate rigidly on the main sequence with a ratio of equatorial speed to Keplerian of 20\%. Angular momentum transport, especially by shear mixing and Eddington Sweet circulation, was followed throughout the evolution, but magnetic torques were neglected. As a result, the collapsing helium core rotated sufficiently rapidly to produce a disk outside of a massive black hole once about 140 \text{ M}_\odot of the 180 \text{ M}_\odot core of helium and heavy elements had collapsed. Fryer et al. (2001) speculated that the accretion of the remaining 30–40 \text{ M}_\odot might produce a very bright, lengthy GRB.

We have recalculated the evolution of similar stars, but with magnetic torques (Spruit 2002) included in the simulation. Models Z250A, B, and C are stars with zero metallicity and a mass at the time they formed of 250 \text{ M}_\odot. They differ in the amount of angular momentum each had on the main sequence. Z250A had 0.75 \times 10^{54} \text{ erg s} corresponding to a rotation rate of 170 km s^{-1}, or 12\% Keplerian. Models Z250B and Z250C had 1.0 \times 10^{54} \text{ erg s and 1.5 \times 10^{54} erg s} of angular momentum and rotational speeds of 220 km s^{-1} (15\% Keplerian) and 310 km s^{-1} (19\% Keplerian). These made helium cores of 143 \text{ M}_\odot, 166 \text{ M}_\odot, and 222 \text{ M}_\odot respectively, all of which collapsed directly to black holes following helium depletion. Unlike in Fryer et al. (2001) however, none of these helium cores had sufficient angular momentum to make a disk around a black hole anywhere in their interior. Because mass loss was neglected in these models, the angular momentum lost from the helium cores of these stars due to magnetic coupling instead ended up concentrated in the outer part of their hydrogen envelopes.

Figure 3 shows the evolution of the angular momentum in Model Z250B. The evolution of the other two models was similar. Inadequate angular momentum exists in the helium core.
to form a disk but, for Model Z250B, the outer 16 $M_\odot$ can still do so. As in the tidally locked red supergiant case, the collapse timescale for this material is days to months, so a high energy transient of around $10^{51}$ erg s$^{-1}$, possibly boosted by beaming, could exist for that time.

It should be noted, however, that mass loss is even more uncertain in these models than in the others. Due to rotationally induced mixing, the envelopes of all three models were appreciably enhanced in C, N, and O and thus were red supergiants when they died. Neglecting mass loss in such a situation is probably not justified. Also there may be other mechanisms for losing the envelopes of such massive stars besides line- and grain-driven mass loss (Smith & Woosley 2006).

3.4. Helium Stars in Binaries

Helium stars in close tidally locked binaries have been frequently invoked as progenitors for common GRBs (Tutukov & Cherepashchuk 2003; Podsiadlowski et al. 2004; Izzard et al. 2004; Bogomazov et al. 2007; van den Heuvel & Yoon 2007). On the positive side, such events should occur frequently in nature and, if the core of a massive Wolf–Rayet star collapses to a black hole while the surface is forced to rotate at a fraction of its Keplerian speed, disk formation around a black hole is assured. On the negative side, however, the production of a GRB with typical duration $\sim 10$ s requires that the inner part of the helion star rotate rapidly, not just its surface. The inclusion of magnetic torques in tidally locked stars leads to too little rotation to make a disk in that part of the star which might accrete rapidly (Woosley & Heger 2006; van den Heuvel & Yoon 2007). On the other hand, leaving out magnetic torques makes it difficult to produce the spin rates of ordinary pulsars (Heger et al. 2005) and could lead to an overabundance of GRB progenitors.

This is not to say that close binary systems do not produce some form of gamma-ray transient though. The angular momentum in their cores may be adequate to produce a millisecond magnetar, and thus a common GRB, just not a (Type 1) collapsar. If a black hole forms, the accretion of the outer layers of the star may lead to the formation of a disk and GRB much longer than typical. It is this latter possibility that we explore here.

Following van den Heuvel & Yoon (2007), we consider the evolution of helium cores of 8 $M_\odot$ and 16 $M_\odot$ whose surfaces have become tidally locked with a closely orbiting companion.

Van den Heuvel & Yoon (2007) found that the shortest possible periods were 2.05 hr ($\omega = 8.5 \times 10^{-4}$ rad s$^{-1}$) and 2.47 hr ($\omega = 7.1 \times 10^{-4}$ rad s$^{-1}$) for 8 $M_\odot$ and 16 $M_\odot$ helium stars, respectively, and they gave examples of systems containing a compact object and a helium core that might approach these limiting values. An 8 $M_\odot$ helium core in a tidally locked binary with a 0.8 $M_\odot$ companion filling its Roche lobe had a longer period of 7.17 hr ($\omega = 2.4 \times 10^{-4}$ rad s$^{-1}$). Here we calculate two models for each helium core mass. Model 8A has an enforced rotation rate in its outer 0.5 $M_\odot$ of $2 \times 10^{-4}$ rad s$^{-1}$ throughout its evolution. Models 8B, 16A, and 16B have rotation rates of $8.5 \times 10^{-4}$ rad s$^{-1}$, $2 \times 10^{-4}$ rad s$^{-1}$, and $7 \times 10^{-4}$ rad s$^{-1}$, respectively.

Figure 4 shows the evolution of the angular momentum distribution as a function of mass for these four models. During helium burning, magnetic coupling maintains a state of nearly rigid rotation with an angular speed given by the surface boundary condition. For both Model 8A and 16A, this corresponds to a ratio of rotational speed to Keplerian at the surface of $\sim$8%. For Models 8B and 16B, the ratio is $\sim$32%. Roughly the inner 75% (8 $M_\odot$) or 85% (16 $M_\odot$) of the helium star is convective during helium burning and rigid rotation is enforced in that region. The outer part of the star is radiative, but magnetic torques suppress differential rotation. During carbon burning and more advanced stages, the inner core contracts and rotates more rapidly. Magnetic torques are too inefficient to enforce rigid rotation. Later, during carbon burning, the stars ignite a convective helium burning shell which persists until the star dies. This convective shell does not extend all the way to the surface though, but does extend beyond the 0.5 $M_\odot$ at the surface where corotation is enforced. Thus, all stars die with an angular velocity in their helium convective shell given by the surface boundary condition, but have more rapid rotation rates in their cores, due to contraction during advanced burning stages.

Figure 5 shows the corresponding angular momentum in the evolving models. Shear instabilities and magnetic torques transport angular momentum out of the inner core and to the surface. In the absence of a binary companion, the surface would have actually spun up, but would have been removed by mass loss. In the present parameterized calculations though, there is no mass loss and the set rotation rate of the surface absorbs any excess angular momentum delivered to it. Consequently,
Figure 4. History of the angular velocity for 8 $M_\odot$ and 16 $M_\odot$ helium cores in tidally locked binary systems. The two top panels show Models 8A (left) and 8B (right) and the bottom panels show Models 16A (left) and 16B (right). Note the tendency of all but the inner core to rotate with the (imposed) surface angular speed. At late times the core evolves rapidly and rotates differentially.

Figure 5. History of the equatorial angular momentum for 8 $M_\odot$ and 16 $M_\odot$ helium cores in tidally locked binary systems shown in Figure 4. The total angular momentum of the star decreases with time. For Model 8A at helium ignition, it was $9.0 \times 10^{51}$ erg s, but for the pre-supernova star it was $1.6 \times 10^{50}$ erg s.

Figure 6 shows the final distribution of angular momentum in the stars compared with that required to make a disk around a black hole, once the mass interior to the given sample point has
Figure 6. Final angular momentum for 8 $M_\odot$ and 16 $M_\odot$ helium cores in tidally locked binary systems compared to that required to form a disk around a black hole. Models 8B (upper right) clearly could make a disk and a rapidly rotating black hole. Model 16A (lower left) would not. Disk formation in Models 8A and 16B depends on the retention and collapse of a small bit of mass at the surface.

collapsed. Four curves are given. Three are for the minimum angular momentum required to form a disk at the last stable orbit of (1) a non-rotating (Schwarzschild) black hole, (2) a Kerr black hole, and (3) a black hole with rotation given by the actual angular momentum distribution of the pre-supernova star. The fourth curve is the angular momentum distribution in the pre-supernova star. Because the inner parts of the star are not rotating very rapidly, curves (1) and (3) are similar except near the surface. Only where the actual angular momentum lies above curve (3) can a disk form. Material with less angular momentum plunges directly into the hole.

None of the models has enough angular momentum to form a disk in its inner core. Thus a Type 1 collapsar will not occur. The angular momentum in the inner 1.7 $M_\odot$ of the stars is still appreciable, however. Models 8A and 16A would form 1.4 $M_\odot$ (gravitational mass) pulsars with periods of 7.4 ms and 2.6 ms, respectively. Models 8B and 16B would form pulsars of 3.2 ms and 1.5 ms. Model 16B thus qualifies as a “millisecond magnetar” candidate and might power a common GRB if a pulsar is able to form before accretion turns it into a black hole. Models 8B, 16A, and 16B could also make powerful pulsar-powered supernovae. Model 8A and other more slowly rotating systems probably would not.

Of greater interest for the present paper, however, is the large angular momentum in the outer layers of three of the models. These would be relevant if the center of the star collapsed to a black hole rather than a millisecond pulsar. Model 8A has angular momentum sufficient to form a disk in its outer 0.074 $M_\odot$. Two other models (Table 1) have similar large rotation in their surface layers. These results are consistent with those of van den Heuvel & Yoon (2007) who found that their most rapidly rotating 8 $M_\odot$ and 16 $M_\odot$ helium cores ended their lives with $j$ in outer layers of $3.7 \times 10^{17}$ cm$^2$ s$^{-1}$ and $6.0 \times 10^{17}$ cm$^2$ s$^{-1}$. The radius and gravitational potential of the high angular momentum surface layers allows an order of magnitude estimate of the free-fall timescale (Table 1), about 100 s.

The tidal interaction actually acts to brake the rotation of the surface layers compared to what they would have had in a star without mass loss and no companion star. To illustrate this, Model 8C was calculated, starting from the rigidly rotating helium burning stage of Model 8B (total angular momentum $3.6 \times 10^{51}$ erg s), but with no surface boundary condition and no mass loss. That is, the rotation rate of the surface layers was allowed to adjust to be consistent with whatever angular momentum was transported to them. Without mass loss, the star was forced to conserve angular momentum overall and the very outer layers ended up rotating very rapidly (Figure 6). The angular speed, rather than being $\omega = 7.5 \times 10^{-4}$ rad s$^{-1}$ was $3.7 \times 10^{-3}$ rad s$^{-1}$. In fact, the outer tenth of a solar mass rotated so rapidly that it would be centrifugally ejected. In a realistic calculation, this matter and more underlying matter would probably have been ejected as a disk or a centrifugally boosted wind. The deep interior still lacked sufficient angular momentum to form a disk around a black hole, but the amount of surface material that could form a disk (if mass loss did not remove it) was significant, about 2 $M_\odot$, comparable to that in Model 8B. Two other models like 8C were calculated that included mass loss appropriate for a Wolf–Rayet star at solar metallicity and one-tenth that value. The first ended up with a final mass of 3.95 $M_\odot$ and no surface layers with sufficient angular momentum to form a disk. The second ended up with a mass of 7.09 $M_\odot$ and still had enough angular momentum in its outer solar mass to make a disk.
So the major role of the close companion in the calculations done here is to preserve the angular momentum in the outer layers that might otherwise be removed by mass loss. A companion may also be essential so that the helium core rotates rapidly in the first place, following the loss of the star’s hydrogen envelope. When magnetic torques are included in the calculation, the helium cores of supernova progenitors that are red and blue supergiants rotate too slowly for any portion of that core to make a disk. A close companion could either preserve angular momentum in the core by removing the envelope very early in the evolution or add angular momentum by tidal locking later on.

4. CONCLUSIONS

Tables 1 and 2 summarize the wide variety of transients that can be produced by Type 3 collapsars. In Table 1, \( M_{\text{disk}} \) is the amount of mass capable of forming a centrifugally supported disk around a black hole with a Kerr parameter given by accreting all the mass interior to \( M_{\text{disk}} \) and \( R \) is the range of stellar radii where that mass exists. The accretion timescale has been estimated using the radius for the center of mass of \( M_{\text{disk}} \). The luminosity has been estimated by multiplying the effective accretion rate (mass/timescale) by 1% \( c^2 \). This assumes 10% efficiency for making a jet and 10% efficiency for converting jet energy into hard radiation. Most models produce extreme Kerr black holes (\( a = 1 \)), so the efficiencies for converting accretion energy into jet energy could be higher than assumed here (Tchekhovskoy et al. 2011). On the other hand, Suwa & Ioka (2011) estimate a large loss of energy in penetrating what is left of the envelope so the radiative efficiency could be lower.

The numbers in the table are only order of magnitude estimates. Table 2 gives the estimated pulsar period formed in the stellar collapse assuming the angular momentum that exists in the inner 1.7 \( M_\odot \) of the core, a final gravitational mass of 1.4 \( M_\odot \), and a moment of inertia of 0.5 \( M_\odot \) \( R_\odot^2 \) (Heger et al. 2005). If a black hole forms before the proto neutron star has radiated away most of its gravitational binding energy, the rotation rate will be slower as will the rotational kinetic energy available for explosion. \( M_{\text{pre-SN}} \) and \( M_{\text{He-core}} \) are the masses of the pre-supernova star and its helium core, respectively, and \( M(j > j_{\text{crit}}) \) is the Lagrangian mass coordinates of the stellar layers that can form a centrifugally supported disk. The Kerr parameter, \( a \), is what would develop if the entire pre-supernova, including its rapidly rotating outer layers, collapsed to a black hole. In cases where it exceeds unity, it has been capped at 1. The Kerr parameter for the helium core alone is \( a_{\text{He}} \). \( BE(j > j_{\text{crit}}) \) is the net binding energy, in units of \( 10^{59} \) erg, of the material that could form a disk.

A range of masses can form disks and a large range of timescales characterize the accretion, hence the possible luminosities span many orders of magnitude. The shorter brighter transients from Wolf–Rayet stars in tidally locked binaries might comprise an interesting subset of long, but otherwise ordinary GRBs, as others have noted. This channel could be especially important in regions where high metallicity and high mass loss preclude the production of GRBs by solitary stars. The mass of \( ^{56}\text{Ni} \) produced in the collapsar model is sensitive to the temperature, density, timescale, and ejection fraction of the disk and is difficult to estimate. The lower accretion rate, larger black hole mass, and smaller Kerr parameter for the models presented here, however, will give lower temperatures and densities in the disk (Popham et al. 1999). Below about 0.01 \( M_\odot \) \( s^{-1} \), the nature of the accretion changes and the disk is no longer neutrino dominated. A thicker disk might qualitatively change the nature of the transient (A. I. MacFadyen 2009, private communication). It is thus reasonable to expect that the \( ^{56}\text{Ni} \) production, per solar mass of material accreted, will be different here and perhaps much smaller. These bursts might not be accompanied by supernovae (e.g., Gal-Yam et al. 2006).

On the longer end, blue and red supergiants will produce transients of order \( 10^4 \)–\( 10^5 \) s and \( 10^6 \)–\( 10^7 \) s, respectively. These could result from either tidally locked systems or more distant systems with low metallicity and mass loss. These fainter and potentially more common systems may not have been detected yet and certainly should be searched for. They could easily be confused with flaring gamma-ray blazars (Woosley 2012; Burrows et al. 2011; Quataert & Kasen 2011; Bloom et al. 2011; Levan et al. 2011), but would differ in that they only happen once and would be associated with regions of massive star formation, not particularly galactic nuclei. They too would probably not be accompanied by supernovae and might have a different beaming factor and spectrum from ordinary GRBs. The black holes produced in these supergiant progenitors would frequently be rotating at near the maximum value (Figures 1 and 2).

Regarding the specific events mentioned in the introduction, we would attribute both Sw-2058+0516 and Sw-1644+57 to black hole formation in red supergiants, probably tidally locked (Table 1) and GRB 101225A to black hole formation in either a blue supergiant or tidally locked Wolf–Rayet binary. In the latter case, the Wolf–Rayet stars would either need to have suffered extensive mass loss just prior to collapsing or have large radii to explain the radius inferred from a blackbody. This is not a
problem since radii as large as 30 solar radii have been computed by Yoon et al. (2010).

The chief argument against such an interpretation is the proximity of Sw-1644+57 to a galactic nucleus (Bloom et al. 2011). However, Sw-2058+0516 has not yet been shown to be associated with a galactic nucleus and neither host galaxy is an active one (Cenko et al. 2012). One expects ~15% of GRBs to be associated with galactic nuclei (Fruchter et al. 2006), so additional statistics may help to discriminate the models. Furthermore, if these events are interpreted as tidal disruptions of stars by massive black holes, then they should appear in a restricted set of galaxies, and never from the most massive black holes, where the disruption takes place within the event horizon. Therefore, a burst from the nucleus of a very massive galaxy might be more likely to be a collapsar, rather than a tidal disruption.

An exciting prospect is that the first generations of stars, those with metallicities from 0 to 0.1 solar might be studied directly using the hard X-rays they emit when they die. While our predictions are still clouded by the vagaries of mass loss and the explosion mechanism, our studies predict that the fraction of massive stars emitting such bursts could be substantial, essentially limited only by the fraction that make black holes promptly. If none make black holes promptly, then the death of every massive star must make a supernova, though perhaps a faint one. This too is an interesting possibility worth further exploration.

Because of their long-duration and potentially high event rate, it is possible that several Type 3 collapsars will be visible in distant galaxies at any one time. Madau et al. (1998) estimate that 20 core-collapse supernovae occur each year in a field of view 4′ × 4′ in the redshift range z = 0, . . . 4. This is about six supernovae per second spread over the whole sky. The observation of GRBs beyond redshift 8 shows that massive stars were dying at an even earlier time. Black hole formation probably occurs in a significant fraction of these supernovae (O’Connor & Ott 2011; Smarrt 2009; Horiuichi et al. 2011), perhaps all those with mass over 20 M⊙ and metallicity less than 10% solar. In order to estimate, crudely, an event rate, assume that prompt black hole formation occurs in 10% of core collapses and 1% of these stars either have such low mass-loss rates or close companions that their outer layers make a disk. Then 0.1% of all massive star deaths would make Type 3 collapsars. For low-metallicity stars, the latter could be an underestimate. The universal supernova rate of 6 s−1 then implies a gamma-ray transient event rate of 0.006 s−1. If each event lasted 104 s, there would ~50 events in progress at all times. Most of these would be at high redshift (low metallicity) and the spectrum would be softer and the duration longer than in the lab frame, so the number of active sources could be higher. On the other hand, beaming could increase the brightness and decrease the event rate significantly. The off-axis events might be detectable, however, by their radio emission (Zauderer et al. 2011).

In an extreme limiting case where 10% of all massive star deaths made Type 3 collapsars with duration 105 s with negligible beaming, one would have ~106 active sources at any one time, or about 1 deg−2. If each source radiated 1041 erg, this could potentially contribute to a “diffuse” cosmological background of soft gamma-rays.

The greatest uncertainty in these results is whether the matter with high angular momentum will get ejected, by mass loss either before or during the explosion, without falling to the center of the star. As Table 2 shows, the binding energy of the critical material is very much less than the kinetic energy of a typical supernova, so a weak explosion or even strong pulsations during oxygen or silicon burning could eject it. It seems unlikely that this would happen all of the time in all sorts of models, so perhaps this enters in chiefly as a major uncertainty in the event rates. We also note that the converse problem, the optical appearance of a “supernova” exploding with only ~1059 erg–1060 erg of kinetic energy, is an interesting one too. One way or another, it seems unlikely that these stars will all disappear without a trace.

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APPENDIX

ESTIMATE OF ACCRETION RATE

Starting from the usual definition of free-fall time,

\[ \tau_{ff} = \frac{1}{\sqrt{2\pi G \rho}} \]

we obtain an order-of-magnitude estimate of the accretion rate from

\[ \dot{M} = \left( \frac{d \tau_{ff}}{dm} \right)^{-1} = \sqrt{18G} \left( \frac{d}{dm} \frac{m}{\rho} \right)^{-1/2} \]

\[ = \sqrt{18G} \left( -\frac{1}{2} \frac{m}{\rho} \right)^{-3/2} \left( \frac{1}{\rho} - \frac{3m}{r^2} \frac{dr}{dm} \right)^{-1} \]

\[ = 6 \left( \frac{2Gm^3}{r^3} \right)^{1/2} \left( \frac{3m}{4\pi r^2 \rho} - 1 \right)^{-1} \]

\[ = 6 \left( \frac{2Gm^3}{r^3} \right)^{1/2} \left( \frac{3m}{4\pi r^2 \rho} - 1 \right) = 6m \left( \frac{8\pi G \rho}{3} \right)^{1/2} \frac{\rho}{\rho - \rho} \]

\[ \dot{M} = \frac{2m}{\tau_{ff}} \left( \frac{\rho}{\rho - \rho} \right) \]

where we used \( \rho(m) = 3m/(4\pi r^3) \) and \( dm = 4\pi r^2 \rho dr \), and \( m \) is the mass coordinate and \( r \) is the radius coordinate of a shell. Note that usually \( \rho(m) > \rho(m) \) in most parts of the star; density inversions can exist at the outer edge of convective regions in mixing-length theory especially in RSGs due to recombination and opacity drops. If \( \rho \ll \bar{\rho} \), as in the case of the outer layers of a BSGs, we obtain \( \dot{M} \approx \frac{2m}{\tau_{ff}} (\frac{\tau_{ff}}{\rho}) \ll \dot{M}_{\tau_{ff}} \), so BSGs may have a more tenuous accretion rate and fainter, softer GRBs than RSGs based on the estimate from \( \tau_{ff} \). On the other hand, the average density of the star is higher as it is more compact, which may be a slight compensation. Density inversions at the edge of RSG envelopes could lead to spikes on accretion rate in this simple approximation.
