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Neutron star binaries and long duration gamma-ray bursts

Andrew J. Levan[1,2⋆], Melvyn B. Davies[2] and Andrew R. King[3]
[1] *Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK.*
[2] *Lund Observatory, Box 43, SE–221 00, Lund, Sweden.*
[3] *Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK.*

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ABSTRACT

Cosmological long-duration gamma-ray bursts (LGRBs) are thought to originate from the core collapse to black holes of stripped massive stars. Those with sufficient rotation form a centrifugally-supported torus whose collapse powers the GRB. We investigate the role of tidal locking within a tight binary as a source of the necessary angular momentum. We find that the binary orbit must be no wider than a few solar radii for a torus to form upon core collapse. Comparing this criterion to the observed population of binaries containing two compact objects suggests that rotation may have been important in the formation of up to 50% of the observed systems. As these systems created a neutron star and not a black hole they presumably did not produce highly luminous GRBs. We suggest instead that they make the subset of GRBs in the relatively local universe which have much lower luminosity.

Key words: Gamma-ray bursts: compact binaries: supernovae

1 INTRODUCTION

The link between long-duration gamma-ray bursts (GRBs) and stellar collapse is now firmly established (Woosley 1993; Hjorth et al. 2003; Stanek et al. 2003). In particular long-duration GRBs appear to originate in type Ic supernovae and frequently in hypernovae (core collapse events with an order of magnitude more energy than classical supernovae). The nature of the short duration ($< 2s$) bursts is far more uncertain, although their origin in populations of all ages (e.g. Gehrels et al. 2005; Berger et al. 2005; Prochaska et al. 2006) can be explained if they are caused by the final merger of a tight binary system of neutron stars (NS) or black holes (e.g. NS-NS, NS-BH). In addition to these two main classes of bursts, which are distinguished primarily based on their observed duration, there is also evidence for further subtypes. For example as well as the very energetic GRBs which originate from high redshifts (e.g. a mean redshift of ~ 2.8; Jakobsson et al. 2006) there is also a further population of low luminosity events which can be seen only in the relatively local universe. The prototype for this class is GRB 980425/SN 1998bw (Galama et al. 1998) which occurred only 35 Mpc away, while GRB 031203/SN 2003lw (at ~ 450 Mpc; Watson et al. 2004; Malesani et al. 2004) and most recently GRB 060218/SN 2006aj (at ~ 130 Mpc; Modjaz et al. 2006; Pian et al. 2006) also lie in this class. These low luminosity events have isotropic equivalent luminosities of only 10^{48-49} ergs compared with energies of up to 10^{54} ergs for the most luminous GRBs. Thus, while the number of observed systems is significantly lower, their space density is likely to be much higher than for the more luminous bursts.

Regardless of the object responsible for the GRB (e.g. NS-NS binary or collapsing star) the most popular model for the creation of the burst is essentially the same - extreme accretion rates on to a newly–formed compact object. This accretion is thought to be fuelled by a massive (0.1-10 $M_{\odot}$) torus which forms if the infalling material has too much angular momentum to accrete directly on to the central compact object. In NS-NS mergers, it is relatively common for mergers to produce a torus (see e.g. Ruffert & Janka 1999;Rosswog & Davies 2002). For massive single stars, it is not clear whether sufficiently high central rotation rates may be maintained to produce a torus on core collapse (e.g. MacFadyen & Woosley 1999;Petrovic et al. 2005), although it has been suggested that rapidly rotating metal–poor stars can retain sufficient angular momentum (Yoon & Langer 2005; Woosley & Heger 2006). Alternatively, binary scenarios suggest a way of removing the envelope and providing a source of angular momentum (e.g. Izzard et al. 2004; Podsiadlowski et al. 2004). We explore this mechanism further in this paper.

Specifically we examine the idea that the core of a massive star may be spun up by tidal locking within a tight binary. The necessary binary separations are a few solar radii or less. The hydrogen envelope of the massive star would therefore have been lost earlier (probably in a common en-

⋆ E-mail: anl@star.le.ac.uk (AJL); mbd@astro.lu.se (MBD); ark@astro.le.ac.uk (ARK)

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velope phase). Systems sufficiently tight may undergo a further period of mass transfer, similar to that seen in Cyg-X2 (e.g. Davies, Ritter & King 2002). We subsequently examine known compact binary systems (NS-NS, NS-WD) and conclude that, at the time of the supernova, approximately 50% may have been sufficiently tight to necessitate the formation of a disc.

We suggest that low and high luminosity GRBs may be distinguished by the formation of either a NS (low luminosity) or BH (high luminosity). The only compact object – compact object binaries discovered so far in the Milky Way consist of neutron stars and white dwarfs. However similar systems, with more massive cores could produce black holes, and thus luminous GRBs.

2 EVOLUTIONARY PATHWAYS TO COMPACT OBJECT BINARIES

Compact binaries consisting of some combination of NS and BH, and possibly white dwarfs (WDs), can be formed via a variety of channels (see e.g. Belczynski et al. 2002). The basic scheme is shown in Figure 1, and is essentially the same as that described in Bhattacharya & van den Heuvel (1991).

The route to forming the compact object binary is thus a relatively close binary system. For the formation of a double neutron star (rather than a NS-WD system) both components must have $M > 8\mathrm{M}_{\odot}$. The initially more massive star evolves more rapidly, leaving the main sequence before its companion and, if the binary is sufficiently close, causing a first incidence of conservative mass transfer. This phase of mass transfer may significantly increase the mass of the secondary (as was the case for J1141-6545 [Davies et al. 2002]). The core of the primary continues to evolve to the point of core collapse and supernova explosion, producing either a neutron star or black hole depending on its mass. Subsequently the second star evolves off the main sequence. As the mass ratio at this point is large, the resulting runaway mass transfer creates a common envelope in which the He core of the secondary and the first neutron star inspiral due to the loss of orbital angular momentum and energy via dynamical friction in the envelope. Eventually this envelope is removed and a He-star – NS system remains (i.e. the hydrogen has now been removed from the system so the final SN is Type I).

The penultimate step in the evolution of compact binaries is the evolution of the He star – NS binary. As the final process prior to the second SN, the evolution of the binary at this stage may have the largest impact on dynamics of the SN upon collapse. In particular the angular momentum of the He-star largely dictates the formation (or not) of a disc upon core collapse. We assume here that the binary is tidally locked at the end of the helium main sequence, this is reasonable since the timescale for synchronisation of the orbit is less than the evolutionary timescale for the Helium star (Hut 1981;Tassoul 1995). Given this, we then calcluate the angular momentum content of the core at the time of core collapse, as discussed in the next section. The evolution of a He-star – NS binary has been investigated in detail by Dewi et al. (2002, 2003). For the very close binaries of interest here the He star essentially always fills its Roche lobe, either on the helium main sequence or in the giant branch. We use a simplistic model in which the subsequent evolution of the orbit is governed by three factors; i) inspiral via gravitational radiation, ii) mass transfer and iii) mass loss via winds. Gravitational radiation always acts to decrease the separation of the two components, while mass loss decreases the total mass of the system and may drive the binary to wider separations. We do not consider the effect of magnetic fields within the star, although they may act to slow the rotation (e.g. Petrovic et al. 2005). This may occur since the core and envelope remain magnetically coupled after the He main sequence, or because of angular momentum loss via stellar winds flowing along the field lines while on the main sequence. The latter effect would be less noticeable at lower metallicity and may explain a bias towards GRB in low metallicity environments (see section 7). The effect of mass transfer when the He star overflows its Roche lobe can be more complex. Matter overflowing the Roche lobe falls onto the already formed neutron star and angular momentum may be ejected from the binary (e.g. via a wind). However, if this material has low specific angular momentum then the system can widen. Indeed, Dewi et al. (2002) find that for massive He stars (i.e. those that form neutron stars) the period typically increases through the He star evolution. Alternatively, mass transfer from the He star may result in the merger of the He star and the neutron star via a delayed dynamical instability if the mass ratio is too extreme.

3 DISCS AROUND NEUTRON STARS AND BLACK HOLES

In the general model discussed above, rotation is a crucial ingredient in the production of a GRB. Too little rotation results in the direct collapse of the progenitor star and will preclude the formation of a torus and thus of a GRB. Here we assume that the material lying just outside the core must be centrifugally supported upon collapse, in order to form an accretion disk outside the innermost stable orbit of the nascent black hole. This criterion can be expressed quantitatively as requiring that the specific angular momentum j of the material just outside the core exceeds $\sqrt{D}GM_{\rm c}/c$, where D is the radius of the orbit required for disk formation in units of Schwarzschild radii (GM/c^2) (e.g. the innermost stable orbit lies at $D = 6$, or ~ 12 km for an 1.4 $M_{\odot}$ BH), $M_{\rm c}$ and the core mass (Podsiadlowski et al. 2004).

Discs around neutron stars can be more difficult to create, since young neutron stars can be markedly larger than the canonical 10 km radius commonly assumed. Therefore the disk must be formed at higher ($\sim 20-50$ km) radius from the newly formed NS. The creation of the disk at a larger radius thus requires greater angular momentum. If this requirement arises from a tidally locked binary, we can show that this in turn demands a correspondingly higher orbital velocity. We assume as described above that tidal locking occurs at the beginning of the Helium main sequence and that, for the late stages of evolution of the He-star (i.e. in the He giant branch) the core decouples from the envelope. In this case, following Podsiadlowski et al. (2004) we can compare the required angular momentum at the time of collapse with that at the edge of the iron core at the start of the

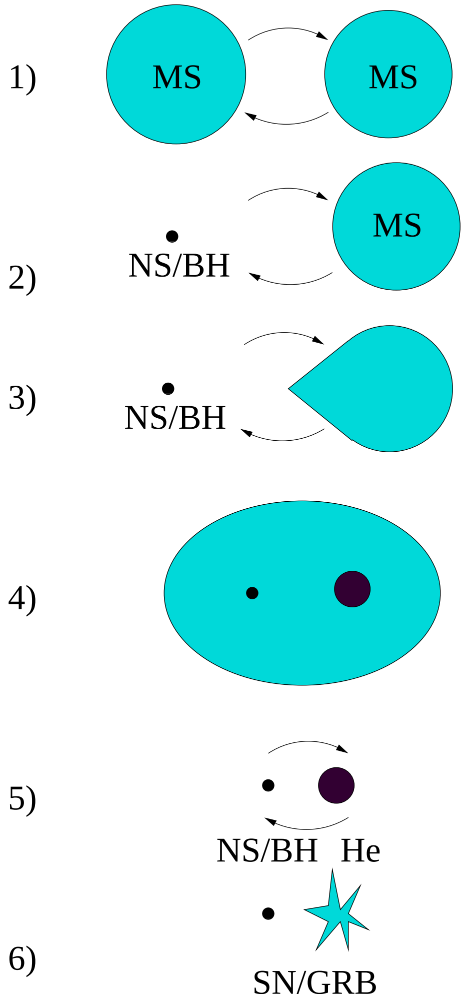

Figure 1. An evolutionary pathway to the creation of a binary containing a rapidly-rotating core-collapse supernova in a tight orbit. The primary evolves first, possibly transferring material to the secondary (stage 1). It then produces a neutron star (NS) or black hole (BH), when it explodes as a core-collapse supernova (stage 2). The secondary then evolves, filling its Roche lobe (stage 3) and transferring material to the NS/BH producing a common envelope phase (stage 4). The NS/BH and He core of the secondary spiral together ejecting the surrounding envelope producing a very compact binary (stage 5). Tidal locking produces a rapidly-rotating He star such that the rotation is significant when the secondary explodes as a core-collapse supernova, with a torus being formed around the central compact object by infalling material.

helium main sequence, and, assuming tidal locking equate this to an orbital frequency (i.e. $\omega = \sqrt{D}GM_{\rm c}/R_{\rm c}^2 c$, where $R_{\rm c}$ is the radius of the iron core). Assuming synchronous rotation, this gives a critical orbital separation

$$a < (4M_{\rm tot}c^2R_{\rm c}^4/9DGM_{\rm c}^2)^{1/3}, \qquad (1)$$

or

$$\left(\frac{a}{R_\odot}\right) < \frac{60}{D^{1/3}}\left(\frac{R_{\rm c}}{R_\odot}\right)^{4/3}\left(\frac{M_{\rm tot}}{M_\odot}\right)^{1/3}\left(\frac{M_{\rm c}}{M_\odot}\right)^{-2/3}, \qquad (2)$$

where $M_{\rm c}$ and $R_{\rm c}$ are the core mass and radius, and $M_{\rm tot}$ is the total mass of the binary. We use here the models of Heger et al. (2002), the key parameters are $M_{\rm c} = 1.7$ M$_\odot$, $R_{\rm c} \sim 0.1R_\odot$, for a He star of mass 7.71 M$_\odot$, this yields a critical separation of ~ 3 R$_\odot$ for the formation of a disc at the innermost stable orbit of a 1.7 $M_\odot$ BH.

4 COMPARISON WITH KNOWN SYSTEMS

We have examined the distribution of separations for the *known* compact binary systems (NS-NS or NS-WD) within our own Galaxy. These are shown in the semi-major axis – eccentricity plane in Figure 2. From the currently–measured orbital parameters it is possible to constrain the pre-explosion parameters of each of the systems. The difference between the currently observed orbital parameters, and those immediately prior to the SN comes from the inspiral of the binary components via gravitational radiation and the effects of the kick imparted to the second NS at the time of the SN. Both of these effects can be accounted for. Initially the inspiral of the orbit can be extrapolated back to the time of the second SN using the equations of Peters (1964) for the time evolution of eccentricity and semimajor axis for a binary. Secondly the range of pre-SN separations can be estimated, since, as the orbit is closed, the NS must return to the point in the orbit at which the SN occurred, i.e.

$$(1 - e_{SN})a < a_{SN} < (1 + e_{SN})a, \qquad (3)$$

where a_{SN} and e_{SN} represent the semi-major axis and eccentricity of the system, immediately after the second SN, as calculated by integrating the Peters (1964) relations back to the characteristic age of the recycled pulsar. The results of this are shown in Table 1, and demonstrate that only modest evolution of the orbit has occurred.

As can be seen in Figure 2 a number of compact binaries have separations which are sufficiently close that, upon collapse material may have been rotating too rapidly to fall directly onto the nascent NS and thus it is expected that a disc will have formed. This represents roughly 50% of the observed population of compact binaries, and the relevant systems are tabulated in Table 1.

However, there are reasons to suspect that this measure of the fraction of compact binaries forming discs may be an underestimate. For example population synthesis models (e.g. Belczynski et al. 2002) show that a large fraction of double neutron star binaries form with orbit separations $\ll 1R_\odot$ and subsequently have merger times of $< 10^6$ years. This population is under-represented in current pulsar surveys since their short lifetimes bias against their discovery even though (by number formed) they may be the dominant population. Such NS-NS binaries *must* at the time of formation of the second NS have had separations small enough to meet the criteria described above, and it is thus reasonable to suspect that disc formation should have occurred in each of these systems at the time of core collapse.

5 NS-NS BINARY FORMATION AND LOW LUMINOSITY GRBS

Figure 2 clearly shows that, at the time of core collapse, several of the observed NS-NS binaries were sufficiently close for centrifugally supported discs to form. Since GRBs are

System	J0737-3039	J1906+0746	J1141-6545	J1756-2251	B2127+11C	B1913+16	B1534+12
M_{total} ($M_\odot$)	2.58	2.61	2.31	2.57	2.71	2.83	2.75
P_{orb} (days)	0.102	0.16	0.20	0.32	0.3	0.3	0.421
a_{orb} ($R_\odot$)	1.3	1.7	1.9	2.7	2.8	2.8	3.3
e	0.088	0.085	0.17	0.18	0.68	0.62	0.274
age (10^8) years	0.5	0.001	0.014	4.4	0.97	1.1	2.5
a_{SN} ($R_\odot$)	1.45	same	same	2.9	3.51	3.25	3.39
e_{SN}	0.10	same	same	0.20	0.74	0.66	0.282
a_{min}, a_{max} ($R_\odot$)	1.3,1.6	1.6,1.8	1.6,2.2	2.2,3.2	0.9,6.1	1.1,5.4	2.4,4.2

Table 1. Properties of compact binaries which may have formed a disc during the second SN explosion. The current orbital parameters are from Champion et al. (2004), Lorimer (2005) and Faulkner et al. (2005) while the a and e immediately after the second SN have been calculated by extrapolating the evolution of the orbit via gravitational radiation (Peters 1964) back over the characteristic age of the pulsar. a_{min} and a_{max} represent the range of plausible separations of the binary at the time of the second SN and can be compared to the critical values for the formation of a disc at different radii as shown in Figure 2

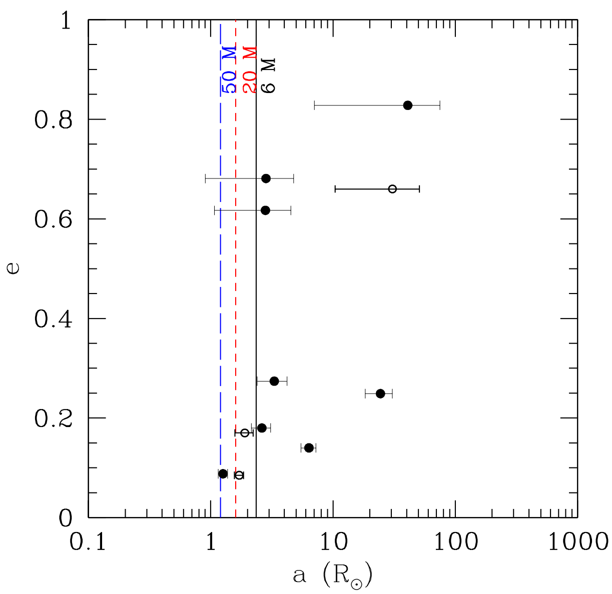

Figure 2. The eccentricity and semi-major axis of observed systems containing either two neutron stars, or a neutron star and white dwarf. The error bars give an indication of the range of separations between the two stars during their orbit. Neglecting the inspiral the separation at the time of the supernova must be taken from this range (see Table 1 for the calculations including the effects of inspiral via gravitational radiation). The three vertical lines represent the critical separations necessary at the time of core collapse for a centrifugally supported disc to have formed at a distance of 6M, 20M and 50M from the newly formed compact object, based on the models of Heger et al. (2002) described in section 3 (where $M = GM_{ns/bh}/c^2$ and is $\sim 12, 40\&$ 100 km for D=6,20 & 50 for a 1.4 $M_\odot$ NS). Lower total masses, as were likely the case of J0737-3039 require slightly tighter orbits, although the orbit is only a weak function of the total mass ($M_{tot}^{1/3}$). If the binary separation is less than this (i.e. to the left of the line) then disc formation is favoured. The data are from Champion et al. (2004) and Lorimer (2005). In cases where the masses of the two components have not be measured 1.4 $M_\odot$ has been assumed. Known NS-NS binaries are indicated with circles, while NS-WD or those with uncertain companions are marked with open circles.

	Galaxy^{-1} yr^{-1}	Gpc^{-3} yr^{-1}
GRBs	1×10^{-7}	1.5
LLGRBs	3×10^{-5}	500
SGRBs	$> 2 \times 10^{-6}$	>30
SN CC	7×10^{-3}	100000
HNe	1×10^{-5}	150
SN Ic	1×10^{-3}	15000
NS-NS	1×10^{-4}	1500
NS-BH	1×10^{-5}	150
BH-BH	3×10^{-5}	450

Table 2. Approximate local rates of different events related to GRBs including Low Luminosity GRBs (LLGRBs - Liang et al. 2006) and short GRBs (SGRBs - Nakar et al. 2005). The rates have been taken (or derived) from Podsiadlowski et al. (2004), Kalogera et al. (2004), Belczynski et al. (2002) and Cappellaro et al. (1999)

commonly thought to originate from similar discs surrounding black holes, it is interesting to investigate whether SN producing discs around newly-formed neutron stars may also produce some form of GRB. The maximum energy released in the accretion of the torus is given by $E = GM_{\rm ns/bh}M_{\rm acc}/R_{\rm ns/bh}$, or $E_{\rm ns} = 3.6 \times 10^{53}(M_{\rm acc}/M_\odot)$ ergs, for a 1.4 $M_\odot$ NS and $E_{\rm bh} = 1 \times 10^{54}(M_{\rm acc}/M_\odot)$ ergs, for any mass BH (since $M_{\rm bh} \propto R_{\rm bh}$).

The extrapolation from disc accretion to gamma-ray luminosity is far from trivial since it requires an assumption about the conversion of accretion luminosity into γ-ray energy. One plausible mechanism of providing this energy is via neutrino-antineutrino annihilation. If this is assumed to be the energy source then the accretion energy can be related to the observed gamma-ray energy via several efficiency factors which account for the conversion of accretion energy to neutrinos, the cross section for neutrino - antineutrino annihilation, the subsequent fraction of energy that is transferred into a baryon free jet, and finally the fraction of this energy which is emitted as gamma-rays (Oechslin & Janka 2006). Following Oechslin & Janka (2006) we assume that the product of the these efficiencies is $\sim 10^{-3}$. Thus the observed luminosities of low luminosity GRBs of $10^{48} - 10^{50}$ ergs can be explained by the accretion of $0.01 < (M_{acc}/M_\odot) < 0.3$ of material from the disc.

There is, of course, a fundamental limit to the mass which can be accreted onto a NS without the consequent accretion induced collapse (AIC) of the neutron star on to a BH (e.g. Dermer & Atoyan 2006). Roughly speaking if the NS mass exceeds ~ 3 $M_\odot$ then a BH forms. The masses of the neutron stars seen in NS-NS binaries are typically close to 1.4 $M_\odot$ ($q \sim 1$), so accretion from the disc has not added dramatically to the mass. We therefore suggest that the result may have been a GRB with a low luminosity of $10^{48} - 10^{50}$ ergs. These systems may therefore be the progenitors of the nearby population of long duration GRBs with lower energies but significantly higher space densities.

As described above, the final step in the formation of a NS-NS binary is the collapse of either a helium or carbon-oxygen core of a massive star in a type Ib/c supernova. Such supernovae only represent a fraction 15% of the total core collapse SN population (Podsiadlowski et al. 2004), and those in tight binary systems only a small fraction of these – approximately 3-10 % based on the ratio of SN Ib/c to compact object – compact object binaries formed (Belczynski et al. 2002)[1] However, it is worth noting that the pathway to NS-NS production described in this paper and the creation of a long-duration GRB both require an SN Ib/c event (e.g. Hjorth et al. 2003; Pian et al. 2006).

From observations of the (relatively small) number of low luminosity GRBs observed to date their local space density is estimated as 700^{+1400}_{-500} Gpc^{-3} yr^{-1}(Soderberg et al. 2006) and 522 Gpc^{-3} yr^{-1}(Liang, Zhang & Dai 2006). This compares with a rate a local rate of NS-NS mergers which lies in the range 200-3000 Gpc^{-3} yr^{-1} (Kalogera et al. 2004; Nakar et al. 2006), although significant uncertainties remain in the derivation of each of these rates it is likely that there are sufficient compact binaries (NS-NS, NS-WD, BH-NS, BH-BH) systems to explain the population of low luminosity GRBs.

6 HIGH MASS ANALOGUES AND COSMOLOGICAL LONG GRBS

The observed compact object – compact object binaries in the Milky Way consist either of WDs or NSs. No BH-NS or BH-WD or BH-BH systems are known. However, it is expected that they are formed in moderate numbers; they are simply harder to detect compared to NS-NS systems which have been found via the radio emission from the recycled pulsars. BH-BH systems can be formed via the same channel as that shown in Figure 1 but with initially higher main sequence masses. In the common model for the creation of GRBs a nascent BH at the core of the massive star is essential. Thus, more massive versions of the systems which formed the observed NS-NS binaries are candidates for the formation of classical long-duration GRBs.

In this context it is reasonable to examine the parameter space which may allow the formation of a rapidly rotating black hole within tidally locked binary systems. In particular, for two massive stars, both of which create a BH we wish to know whether both of the SN could plausibly produce a GRB or if the presence of a compact object prior to the GRB forming SN aids the production of GRBs.

Figure 3 shows constraints on the radius of the secondary object such that it remains within its Roche lobe at the critical orbital separation. If both the He star and the companion overflow their Roche lobes then a further common envelope results, and the most likely scenario is a merger of the He star and the companion. For this constraint to be met the radius of the secondary must be $\gtrsim 1$ $R_\odot$. Thus only low-mass main-sequence stars could remain within their Roche lobes in these binaries. However, should the companion be a compact object (BH or NS) at the time when the progenitor He star enters the He main sequence then the evolution will proceed as described in section 2. In this scenario it is worth noting that the creation of a BH-BH system can aid the production of a GRB in two further ways. Initially the critical rotation periods can be attained at larger separations for more massive companions. In addition, mass transfer from the star is less likely to lead to a delayed dynamical instability when the secondary is a black hole. This is because the mass ratio is lower with a more massive black hole companion rather than a neutron star.

In some cases, when either the mass ratio is too extreme, or the He – NS/BH separation is too small following the common envelope, the binary may merge (e.g Fryer & Woosley 1998), such cases can also plausibly create GRBs by either accretion onto the BH in He – BH systems (Fryer & Woosley 1998), or by merger of two He stars if the masses are sufficiently similar (Fryer & Heger 2005; Dewi et al. 2006). Given that under our criteria a reasonable fraction of the observed systems would have formed a disc it appears unlikely that all binaries with sufficient angular momentum for GRB production undergo such mergers.

7 DISCUSSION

Several lines of recent evidence have pointed to a preference by GRBs for host galaxies of low metallicity (Fynbo et al. 2003; Fruchter et al. 2006; Stanek et al. 2006). In contrast the systems observed in the Milky Way presumably formed at higher metallicity (probably $\sim Z_\odot$). However, one may expect that similar systems form GRBs more readily in lower metallicity environments, due largely to the effects of mass loss on the evolution of the binary. Mass loss from both stars on the main sequence will drive the binary to wider orbits, reducing the fraction of binaries which come into contact at any stage and also those which are sufficiently tight for disc formation upon core collapse. Additionally, mass lost by the Helium star on its main sequence is lost along the magnetic field lines and carries matter to large radii, losing angular momentum from the stellar core and braking its rotation. At lower metallicities the low mass loss rates thus favour more rapid core rotation. Finally, mass loss from the individual stars can dictate the remnant left (NS or BH). In lower metallicity environments the lower mass loss rates thus leave the binary in a closer orbit, and with more massive stellar cores, which collapse to form BHs. Thus lower metallicity will favour the production of GRBs, in agreement with observations.

One consequence of a supernova within a close binary

[1] Note: this is formally a lower limit on the ratio of binary to single SN Ib/c, since a fraction of NS-NS binaries are disrupted on formation of the second NS. This fraction is likely to be small for very tight binaries but larger for wider systems.

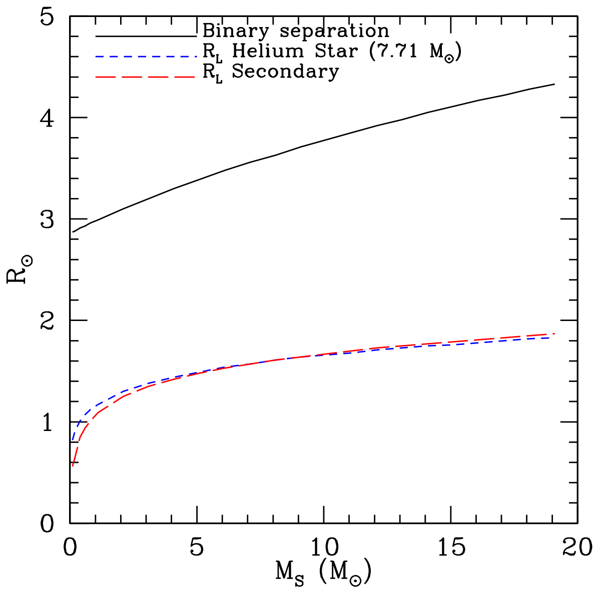

Figure 3. The maximum separation allowed for binaries containing a helium core of a massive star, as a function of secondary mass, such that core collapse of the helium star leads to the formation of a torus of material around the central core, assuming that the system is tidally locked. The Roche lobe radii for the two stars are also shown. As can be seen, main sequence stars with radii $> 1R_{\odot}$ cannot fit within their Roche lobes, and, assuming $M \propto R$ this sets a mass limit of ~ 1 $M_{\odot}$ on the mass of a main sequence companion. However, should both stars overflow their Roche lobes a common envelope would follow and, most likely the resulting system would merge.

is that the outflowing supernova ejecta must pass the older NS. For close binaries the density at the radii of the NS is moderately high and thus, even though the velocity of the ejecta can be very high the Bondi–Hoyle accretion rate may be significant (see e.g. Broderick 2005). Accretion on to this object may provide a additional source of energy, and thus lightcurve variability, in any SN/GRB formed via this channel.

It is interesting to note that in this model some of these systems can create both a long and a short GRB, with the short burst occurring some time ($< 10^8$ years) after the long burst. We note that the NS-NS systems discussed here are distinct from those found in globular clusters, which have been suggested as short GRB progenitors (Grindlay et al. 2005), since NS-NS systems in globular clusters are formed dynamically and not by the channel described here.

8 CONCLUSIONS

We have examined the role of tidal locking in a tight binary system and its implications for the formation of a centrifugally-supported torus upon core collapse. By examining the distribution of separations of known compact object binaries (NS-NS, NS-WD), we conclude that up to $\sim$ 50% of the systems could, at the time of the second supernova, have been sufficiently rapidly rotating to create a torus upon collapse. We subsequently investigated the implications of these observations for the formation of GRBs. None of the observed systems contain a BH, which is thought to be essential to the formation of the highly luminous GRBs. We suggest that higher mass analogues of the observed systems can form GRBs, but that the collapse of less massive stars leading to neutron stars might result in a lower luminosity GRB, similar to those that have been observed in the local universe.

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