ON THE RARITY OF DOUBLE BLACK HOLE BINARIES: CONSEQUENCES FOR GRAVITATIONAL WAVE DETECTION

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Received 2006 December 1; accepted 2007 January 31

ABSTRACT

Double black hole binaries are among the most important sources of gravitational radiation for ground-based detectors such as LIGO or VIRGO. Even if formed with lower efficiency than double neutron star binaries, they could dominate the predicted detection rates, since black holes are more massive than neutron stars and therefore could be detected at greater distances. Here we discuss an evolutionary process that could very significantly limit the formation of close double black hole binaries: the vast majority of their potential progenitors undergo a common-envelope (CE) phase while the donor, one of the massive binary components, is evolving through the Hertzsprung gap. Our latest theoretical understanding of the CE process suggests that this will probably lead to a merger, inhibiting double black hole formation. Barring uncertainties in the physics of CE evolution, we use population synthesis calculations and find that the corresponding reduction in the merger rate of double black holes formed in galactic fields is so great (by ~500) that their contribution to inspiral detection rates for ground-based detectors could become relatively small (~1 in 10) compared to double neutron star binaries. A similar process also reduces the merger rates for double neutron stars, by a factor of ~5, eliminating most of the previously predicted ultracompact NS-NS systems. Our predicted detection rates for Advanced LIGO are now much lower for double black holes (~2 yr⁻¹), but are still quite high for double neutron stars (~20 yr⁻¹). If double black holes were found to be dominant in the detected inspiral signals, this could indicate that they mainly originate from dense star clusters (not included here) or that our theoretical understanding of the CE phase requires significant revision.

Subject headings: binaries: close — black hole physics — gravitational waves — stars: evolution — stars: neutron

1. INTRODUCTION

A number of ground-based gravitational wave detectors are already in operation (TAMA, GEO, and LIGO) and some are approaching an operational phase (VIRGO). These instruments have provided the first upper limits on signals for some potential sources of gravitational radiation (Abbott et al. 2005a, 2005b, 2005c). In this work we discuss the likelihood of detecting the gravitational wave signature of double compact object mergers. The most promising candidates include double neutron stars (NS-NS), double black holes (BH-BH), and mixed systems containing a black hole and a neutron star (BH-NS). Only NS-NS binaries have been so far discovered in the Galaxy electromagnetically, and therefore only for this population are there observational estimates of merger rates that can be translated into detection rates for a given detector (see Kalogera et al. [2004] and Kim et al. [2006] for the most recent estimates). The theoretical studies have been carried out most often via population synthesis methods, which allow for a self-consistent evolution of massive stars leading to the formation of all three populations of compact objects. The early work was conducted by a number of groups (e.g., Lipunov et al. 1997; Belczynski et al. 2005a; De Donder & Vanbeveren 1998; Bloom et al. 1999; Fryer et al. 1999; Belczynski & Bulik 1999; Nelemans et al. 2001), and the different results were summarized and discussed in Belczynski et al. (2002b, hereafter BKB02).

Since our initial work (BKB02), our group has been working intensively for several years to understand issues involved in the formation of double compact objects and to identify the most important (and usually uncertain) processes involved in the evolution of massive stars. As a result, we have created a much refined and updated population synthesis model (Belczynski et al. 2007). This model is now used to calculate the merger rates of double compact objects and to reexamine the chances for detection of gravitational waves from double compact object inspirals and mergers. New results, in the context of gravitational waves and double compact object mergers, have recently been reported in O’Shaughnessy et al. (2007a, 2007b). The results of the above studies are complementary to those reported here. O’Shaughnessy et al. (2007b) predominantly conducted a broad study of the parameter space and applied a number of empirical rate constraints on population synthesis models; here we discuss the specifics of binary evolution leading to the formation of double compact objects, we highlight the importance of CE evolution in the Hertzsprung gap for the inspiral of double compact objects, and we present updated detection rates in the context of our input physics. In this study we focus, in particular, on BH-BH binaries, as the results have changed significantly for this population and are of great importance for LIGO. A thorough discussion of changes (not crucial in the context of gravitational radiation sources) for NS-NS and BH-NS populations will be presented in a forthcoming paper in the context of the progenitors of short-hard gamma-ray bursts (GRBs) in Belczynski et al. (2007).

2. MODEL

Binary population synthesis is used to calculate the merger rates and properties of double compact objects. The formation
of double compact objects is modeled via binary evolutionary processes that take place without considering the effects of stellar dynamical processes associated with the formation of such systems in globular clusters. The formation of binary compact objects in dense stellar environments is currently under intense investigation (see Portegies Zwart & McMillan 2000; O’Leary et al. 2006).

Our population synthesis code, StarTrack, was initially developed for the study of double compact object mergers in the context of GRB progenitors (Belczynski et al. 2002a) and gravitational wave inspiral sources (BKBB02). In recent years StarTrack has undergone major updates and revisions in the physical treatment of various binary evolution phases and especially mass transfer phases. The new version has already been tested and calibrated against observations and detailed binary mass transfer calculations (Belczynski et al. 2007) and has been used in various applications (e.g., Belczynski & Taam 2004; Belczynski et al. 2004, 2005). The physics updates that are most important for compact object formation and evolution include a full numerical approach to orbital evolution due to tidal interactions, calibrated using high-mass X-ray binaries and open cluster observations; a detailed treatment of mass transfer episodes fully calibrated against detailed calculations with a stellar evolution code; updated stellar winds for massive stars; and the latest determination of the natal kick velocity distribution for neutron stars (Hobbs et al. 2005). For helium star evolution, which is of a crucial importance for the formation of double neutron star binaries (e.g., Ivanova et al. 2003; Dewi & Pols 2003), we have applied a treatment closely matching the results of detailed evolutionary calculations. If the helium star fills its Roche lobe, the systems are examined for the potential development of a dynamical instability, in which case they are evolved through a CE phase; otherwise, a highly nonconservative mass transfer ensues. We treat CE events using the energy formalism (Webbink 1984), where the binding energy of the envelope is determined from the set of He star models calculated with the detailed evolutionary code by Ivanova et al. (2003). The progenitor evolution and the Roche lobe overflow episodes are now followed in much greater detail. We note significant differences from our earlier studies. For a detailed description of the revised code, we refer the reader to Belczynski et al. (2007).

The most important change in the context of double compact object formation reflects the treatment of the dynamically unstable mass transfer and evolution into the CE phase. Previously (e.g., BKBB02 and earlier work), we have allowed for the possibility of binary survival when the CE was initiated by a star crossing the Hertzsprung gap (HG). Once the system evolved into the CE, it was determined whether a system emerges as a tight post-CE binary or produces a single, rapidly rotating star as a result of a binary merger. However, a HG star does not have a clear entropy jump at the core-envelope transition (Ivanova & Taam 2004). Therefore, once a companion is engulfed within a HG star, there is no clear boundary where the inspiral ceases, and consequently a merger is expected (see, e.g., Taam & Sandquist 2000). In this case, the HG star is insufficiently evolved for the systems to merge, even though it may be energetically possible to unbind the envelope. It is expected that the orbital decay timescale is shorter than the mass-loss timescale. This is a direct result of the absence of steep density gradients above the nuclear-burning shells in this evolutionary stage, where a nonnegligible amount of mass lies above the core, facilitating rapid decay of the orbit. In the current StarTrack modeling, we assume that any CE involving a HG donor eventually leads to a binary component merger and to the formation of a single object. Since many potential double compact object progenitors evolve through the CE phase (see BKBB02 and their Table 3), we have reexamined the double compact object populations in view of these mergers expected in CEs with HG donors. In particular, it is found that close BH-BH systems are affected the most, as the majority of their potential progenitors evolve through the CE phase with a hydrogen-rich HG donor. It is also found that about half of the progenitors of NS-NS systems evolve through the CE phase with helium-rich HG donors. These systems were allowed in our previous work to form very close, ultracompact, NS-NS systems. With this study, we now recognized that these systems are not likely to survive the CE phase, and we treat them as mergers (inhibiting significantly ultracompact NS-NS formation) in our reference model. However, we also present alternative models in which we apply the CE energy formulation, even in the case of HG donors, to test this uncertain phase of binary evolution.

Another important change reflects the treatment of accretion onto compact objects in CE phases. In some cases the CE phase may be initiated by a star that has evolved beyond the HG (e.g., red giant or massive core helium–burning star). Up to now, the full Bondi-Hoyle accretion rate onto compact object (for numerical details see BKBB02) was utilized. On average, it resulted in the accretion of ~0.4 $M_\odot$ onto NSs and up to several solar masses onto BHs. However, we have recognized that if such efficient accretion is allowed, the predicted masses of NSs in NS-NS systems will always be too high as compared with masses for the observed Galactic systems ($\gtrsim 1.35 M_\odot$; Thorsett & Chakrabarty 1999). Motivated by this observation and by multidimensional hydrodynamical calculations that favor mass accretion rates lower than Bondi-Hoyle (e.g., Ruffert 1999), for our reference model we allow only for smaller amounts of mass gain (0.05–0.1 $M_\odot$) in CE phases. The specific values were chosen to be sufficient to (mildly) recycle a NS (e.g., Zdunik et al. 2002; Jacoby et al. 2005). Since such small amounts of accreted mass may not be very realistic in the case of BHs, we also present a model with full Bondi-Hoyle accretion.

3. RESULTS

Evolution leading to the formation of a BH-BH binary involves a number of stages that allow two massive stars to evolve to close proximity and to form a bound BH-BH system. Here we are interested only in those binaries that form BH-BH systems on very tight orbits, so the timescale for inspiral due to gravitational radiation is shorter than 10 Gyr. Only these BH-BH systems can

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### TABLE 1

<table>
<thead>
<tr>
<th>Formation Channel (Model)</th>
<th>Relative Efficiency$^a$ (%)</th>
<th>Evolutionary History$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHBH:01 (A, B)............</td>
<td>50 NC:a $\rightarrow$ b, SN:a, SN:b</td>
<td></td>
</tr>
<tr>
<td>BHBH:02 (A, B)............</td>
<td>25 SN:a, SN:b</td>
<td></td>
</tr>
<tr>
<td>BHBH:03 (A, B)............</td>
<td>13 SN:a, CE:b $\rightarrow$ a, SN:b</td>
<td></td>
</tr>
<tr>
<td>BHBH:04 (A, B)............</td>
<td>12 NC:a $\rightarrow$ b, SN:a, NC:b $\rightarrow$ a, SN:b</td>
<td></td>
</tr>
<tr>
<td>BHBH:05 (C)............</td>
<td>65 NC:a $\rightarrow$ b, SN:a, CE:b $\rightarrow$ a, SN:b</td>
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</tr>
<tr>
<td>BHBH:06 (C)............</td>
<td>28 NC:a $\rightarrow$ b, CE:b $\rightarrow$ a, SN:a, SN:b</td>
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</tr>
<tr>
<td>BHBH:07 (C)............</td>
<td>7 All other</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Normalized to the total number of close BH-BH population in a given model.

$^b$ Sequences of different evolutionary phases for the primary (a) and the secondary (b): (NC) nonconservative mass transfer, (CE) common envelope, and (SN) supernova explosion/core collapse event. Arrows mark the direction of mass transfer episodes.
merge and contribute to gravitational wave detection rates (at least in galaxies with a star formation history similar to the Milky Way). There are a number of processes that can inhibit the formation of BH-BH systems. The main factors involve mergers resulting from mass transfer episodes (a single merger remnant is formed), binary disruption upon the formation of a BH due to mass loss, and the potential natal kick that a BH may receive. However, it is important to realize that in some circumstances these same processes (e.g., an suitably placed natal kick) can allow the formation of close BH-BH systems. Here we present a set of population synthesis models that allow investigation of the effects of those binary evolution elements most important for BH-BH formation. Model A is our reference model, with input physics described in detail in Belczynski et al. (2007), and the most important new elements relevant to double compact object formation are emphasized in § 2. Other models are examined with only one input parameter changed compared to the reference model. In model B, we allow for full hypercritical (Bondi-Hoyle) accretion onto compact objects (see BKB02 for the details of the implementation). In models A and B, CE events with both hydrogen-rich and helium-rich HG donors are assumed to lead to mergers (as explained in § 2). However, in model C, we allow for possible survival of the binaries through such CE events and apply the standard CE energy formulation; this model is the one closest to our reference/standard models in past synthesis studies by our group (e.g., BKB02).

The major formation channels for close BH-BH binaries are illustrated in Table 1. In models A and B, BH-BH formation typically does not involve CE phases, but consists of nonconservative mass transfer episodes and supernovae/core collapse events in which BHs are formed (channels BHBH:01, 02, 04). Only in one channel (BHBH:03) is CE evolution encountered, but in this case it involves evolved donors (during core helium burning), and not HG stars. In model C, most BH-BH systems form via evolutionary channels involving CE phases, and in most cases the donors are HG stars (channels BHBH:05, 06). Channels not involving CE phases with HG donors are also found in model C, but they are very rare and are included, among other inefficient sequences, in channel BHBH:07.

The calculated Galactic merger rates for double compact objects are presented in Table 2. The rates are obtained for two different calibrations. First, we have calibrated our results based on the star formation rate. We have adopted a continuous star formation rate for 10 Gyr. In addition, a combined rate of SN II and SN Ib/c estimated for a Milky Way-type galaxy of $2 \times 10^{-2} \text{yr}^{-1}$ is used to obtain an alternative calibration (see Cappellaro et al. [1999] for a Galactic blue luminosity of $L_B = 2 \times 10^{10} L_\odot$). The supernova-based calibration results in merger rates about 1.5 times higher

<table>
<thead>
<tr>
<th>Model</th>
<th>NS-NS (yr(^{-1}))</th>
<th>BH-NS (yr(^{-1}))</th>
<th>BH-BH (yr(^{-1}))</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, LIGO.......</td>
<td>0.003–0.005</td>
<td>0.0002–0.0003</td>
<td>0.0004–0.0006</td>
<td>Reference model</td>
</tr>
<tr>
<td>B, LIGO.......</td>
<td>0.002–0.004</td>
<td>0.0002–0.0003</td>
<td>0.0003–0.0004</td>
<td>Reference model</td>
</tr>
<tr>
<td>C, LIGO.......</td>
<td>0.017–0.025</td>
<td>0.0061–0.0090</td>
<td>0.10–0.15</td>
<td>Reference model</td>
</tr>
<tr>
<td>A, AdLIGO.....</td>
<td>13–19f</td>
<td>0.68–1.1</td>
<td>1.6–2.5</td>
<td>Reference model</td>
</tr>
<tr>
<td>B, AdLIGO.....</td>
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<td>0.82–1.3</td>
<td>1.1–1.8</td>
<td>Reference model</td>
</tr>
<tr>
<td>C, AdLIGO.....</td>
<td>73–109</td>
<td>26–39</td>
<td>439–655</td>
<td>Reference model</td>
</tr>
</tbody>
</table>

**TABLE 3**

**LIGO DETECTION RATES**

<table>
<thead>
<tr>
<th>Model(^a)</th>
<th>NS-NS (yr(^{-1}))</th>
<th>BH-NS (yr(^{-1}))</th>
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\(^a\) Models are presented for initial LIGO (range of 18.4 Mpc) and Advanced LIGO (AdLIGO; range of 300 Mpc).

**FIG. 1.**—Chirp mass distribution for different populations of double compact objects (reference model A). Chirp masses are of the order of $\sim 1.1–1.2 \ M_\odot$ for NS-NS, $\sim 2.5–3 \ M_\odot$ for BH-NS, and $\sim 5–8 \ M_\odot$ for BH-BH mergers. Note the range changes from panel to panel.
than those for the star formation calibration. For models A and B we find that NS-NS merger rates are 7.6–19 Myr\(^{-1}\)/C0, consistent with the most recent empirical estimates (3–190 Myr\(^{-1}\); see Kim et al. 2006). However, they are somewhat lower (as expected) when compared with our earlier estimates (50 Myr\(^{-1}\); see et al. 2002). The rates for binaries containing black holes are significantly lower in models A and B, 0.07–1.4 Myr\(^{-1}\) and 0.01–0.03 Myr\(^{-1}\) for BH-NS and BH-BH systems, respectively. In particular, these rates are much lower than previously reported (8 and 26 Myr\(^{-1}\) for BH-NS and BH-BH systems, respectively, in the standard model in BKB02). The rates for model C, where we allow for survival in a CE with HG donors, although such a survival is considered unlikely (see 2), are closest to our previous calculations. The differences (factor of ~2) with respect to rates presented by BKB02 are a consequence of a number of improvements and updates in the StarTrack code (see 2 and also Belczynski et al. 2007). In this model C again the Galactic merger rates of NS-NS are the highest (∼90 Myr\(^{-1}\)); however, rates for BH-NS (∼4 Myr\(^{-1}\)) and BH-BH (∼10 Myr\(^{-1}\)) mergers are of the same order of magnitude, in contrast to models A and B. We note that the large decrease (factors of ∼300–800) in BH-BH merger rates from model C to models A and B is due to the expectation that CE events with HG donors lead to mergers.

In Table 3 we show the expected detection rates for the initial (current stage) and the advanced (expected in 2014) LIGO. The detection rates were obtained from the predicted Galactic inspiral rates, \(R_{\text{MW}}\) (see Table 2), with

\[
R_{\text{LIGO}} = \frac{4\pi}{3} d_0^2 M_{\text{dis}} \mathcal{R}_{\text{MW}},
\]

where \(\rho_{\text{gal}} = 0.01\) Mpc\(^{-3}\) is the number density of Milky Way-type galaxies that approximates the mass distribution within the LIGO distance range \(d = d_0 (M_{\text{c,deco}}/M_{\text{c,nsns}})^{5/6}\), where \(d_0 = 18.4, 300\) Mpc for the initial and Advanced LIGO, respectively. The distance range estimates were obtained for a binary with two 1.4 \(M_0\) neutron stars with chirp mass of \(M_{\text{c,nsns}} = 1.2 M_0\), and we rescale them for our populations of double compact objects for given chirp masses \(M_{\text{c,deco}}\). The scaling factor is obtained from

\[
M_{\text{dis}} = \left( \frac{M_{\text{c,deco}}}{M_{\text{c,nsns}}} \right)^{15/6}\]

Note that we first calculate the cube of \((M_{\text{c,deco}}/M_{\text{c,nsns}})^{5/6}\) and then take an average over all double compact objects within a given group (e.g., BH-BH). This calculation assumes Euclidean space geometry and a constant star formation rate, while the cosmological effects, relevant for the BH-BH merger Advanced LIGO rate, are discussed by Bulik et al. (2004). The scaling factors \(M_{\text{dis}}\) for different groups of double compact objects are

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**Fig. 2.**—Mass ratio distribution for different populations of double compact object mergers (reference model A). Note that the majority of NS-NS mergers are found with low mass ratios \((q < 0.4)\), while the distribution is rather flat for BH-BH mergers, with 50% of them characterized by high mass ratios \((q > 0.74)\).**

**Fig. 3.**—Compact object masses for different populations of double compact object mergers (reference model A). First- and second-born compact objects are marked with different lines. Note that NS masses peak at ∼1.35 \(M_0\), while BHs are found in a wide range of masses ∼3–11 \(M_0\), with increasing contribution at the higher mass end.
given in Table 2. The specific values for $\rho_{\text{gal}}$, $d_0$, and $M_{c,\text{mns}}$ were adopted from O'Shaughnessy et al. (2007b). For initial LIGO, we find that the rates are too small for detection, in agreement with predictions in our earlier work, now confirmed with the new models. For Advanced LIGO, on the other hand, we expect quite significant detection rates. For physical models (A and B), the detection rate is dominated by NS-NS events ($\sim 20$ yr$^{-1}$), with a small contribution of BH-BH inspirals ($\sim 2$ yr$^{-1}$) and an even smaller contribution of BH-NS mergers ($\sim 1$ yr$^{-1}$). This is a qualitatively new result, as earlier work (e.g., BKB02) expected BH-BH binaries to dominate the detection rates, as demonstrated in model C. In particular, inspiral signals were expected to be detected at much higher rates ($\sim$ hundreds per year; see model C), dominated by populous BH-BH mergers, as compared to the new smaller rates ($\sim$ tens per year; see models A and B) obtained for models with a dominant NS-NS population.

In Figures 1, 2, and 3 we show the chirp mass, mass ratio, and component mass distributions for double compact objects in the reference model (model A), respectively. The figures include data on double compact objects that have merged in 10 Gyr. The numbers correspond to the disk population of a Milky Way-type galaxy with a constant star formation rate of the order of $3.5 M_\odot$ yr$^{-1}$. As expected, chirp masses are highest for BH-BH systems ($\sim 5$–8 $M_\odot$), intermediate for BH-NS mergers ($\sim 2.5$–3 $M_\odot$), and lowest for the lightest NS-NS systems ($\sim 1.1$–1.2 $M_\odot$). The mass ratio distribution is rather flat for BH-BH mergers; however, due to the fact that they start at a rather high value ($q \sim 0.5$), 50% of the systems are found with a BH of similar mass ($q > 0.74$). Mass ratios for BH-NS are generally low ($q < 0.2$), with the BH being the much more massive component in a given system. For most NS-NS mergers, the mass ratios are rather high ($q > 0.9$), since usually two NSs have very similar masses. Component masses in BH-BH systems are found in a wide range (3–11 $M_\odot$), although most BHs in the merging population are characterized by a rather high mass ($\sim 7$–10 $M_\odot$). For NS-NS systems the majority of component masses are confined to a narrow range (1.1–1.5 $M_\odot$), with a small contribution of heavy NSs ($\sim 2 M_\odot$). For mixed BH-NS mergers, the masses are high for the BH and low for the NS, explaining the rather extreme mass ratio distribution. Note that for some systems the first-born compact object is a NS, and not a BH. This is due to a mass ratio reversal occurring during the mass transfer phase, leading to mass loss from the primary (NS formation) and the rejuvenation of the secondary (BH formation).

In Figures 4, 5, and 6 we present similar distributions for model C. Since the formation of close BH-BH and BH-NS systems is much more efficient (although probably unphysical) in this model, a much higher number of these systems is evident in the distributions. As compared to our new reference model, chirp masses in model C for BH-BH ($\sim 3$–8 $M_\odot$), BH-NS ($\sim 1.5$–4 $M_\odot$), and NS-NS ($\sim 1.1$–1.8 $M_\odot$) are distributed more evenly and over a wider range. This is due to the fact that in this
model many more primordial binaries (with different initial properties) are allowed to contribute to the formation of double compact objects. Mass ratios for BH-BH are found evenly distributed over $q > 0.5$, with a tail in the distribution extending to slightly lower values ($q \sim 0.3$). For BH-NS systems, the majority of mass ratios are small ($q \sim 0.1-0.4$), while for NS-NS systems, mass ratios are rather large ($q > 0.9$), similar to model A. Individual component masses are distributed much more evenly than in the reference model for BH-BH mergers. For BH-NS systems, component masses tend to be much smaller in model $C$ ($\sim 2-4 \, M_\odot$) than in the reference model ($\sim 8-11 \, M_\odot$). For NS-NS systems, the component masses are similar to the reference model, with an increased contribution of high-mass NSs.

We note that model $B$, with full Bondi-Hoyle accretion, is inconsistent with observed NS masses in Galactic NS-NS binaries. The masses of the (second formed) NSs in this model are found between $\sim 1.4-1.8 \, M_\odot$, while observed masses are estimated to be $\sim 1.35 \, M_\odot$ (for more details, see K. Belczynski et al. 2007, in preparation). For BH-BH systems, only $\sim 13\%$ of these evolve through potential CE accretion (see Table 1). This may increase the BH masses by a few solar masses, thereby shifting the mass distributions to slightly higher values.

4. DISCUSSION

We have presented new results for double compact object mergers with special emphasis on BH-BH systems. We identify an evolutionary process that can drastically decrease the BH-merger rates predicted from population synthesis models of binaries in galactic fields, namely, mergers of binaries in the first CE phase, where the donor star is in the HG, which corresponds to the majority of potential BH-BH progenitors considered in earlier work. The new mergers rates for these systems are significantly lower ($\sim 500$) than previously predicted (e.g., model $C$ here and BKB02). As a consequence, BH-BH mergers could become only a small contributor ($\sim 1$ in 10 detections; see models A and B; see also O'Shaughnessy et al. 2007b) to inspiral detection rates for ground-based detectors such as LIGO, in contrast to past predictions in which the BH-BH inspiral strongly dominated the detection rates.

If our understanding of the stellar structure of HG stars or the physics of ejection of a CE is incomplete, and massive systems with HG donors survive the CE phase, forming BH-BH systems, it is predicted that BH-BH inspirals will instead dominate detection rates (see model $C$). Therefore, once a sizable number of inspiral signals have been detected (Advanced LIGO; see Table 3), it may be possible to test this crucial phase of binary evolution leading to the formation of BH-BH systems. Since the observed chirp mass distribution is a very sensitive function of the model of binary evolution, it can lead to further constraints on other processes important for the formation of BH-BH systems (Bulik & Belczynski 2003; Bulik et al. 2004). For example, the orientation and magnitude of the spin of a compact object is an important factor in the search for a gravitational radiation signal from inspiraling binaries, since it affects both the shape and amplitude of the signal. An initial estimate of compact object spins via population synthesis was presented by O'Shaughnessy et al. (2005), who identified accretion in the CE phase as a major contributing factor that can significantly increase spins of compact objects. These early results need to be reassessed, since (1) now only very few BH-BH progenitor systems evolve through a CE (see Table 1), (2) for systems evolving through a CE the so far applied Bondi-Hoyle accretion model may result in overestimates of the accretion and spin-up rates (see § 2), and (3) during the stable mass transfer phases, the spin-up requires recalulation to take into account the possibility that the BH can accept mass at rates $\gtrsim 100$ times critical (Eddington) accretion rates (e.g., Abramowicz et al. 1988; Ohsuga et al. 2002). A model for BH spin evolution has been developed (Belczynski et al. 2007).

One additional calculation was performed to examine the effect of CE treatment on our main result, i.e., the drastic merger rate decrease of BH-BH binaries. We have applied an alternative prescription for the CE treatment involving explicit angular momentum conservation with implicit energy conservation (see Nelemans & Tout 2005). There is only a small change for BH-BH rates, as the CE phase is involved in the formation of only a minor fraction of these binaries (see Table 1).

As discussed throughout this study, the decrease in merger rates is smaller for BH-NS and NS-NS binaries than for BH-BH systems. This originates from the fact that, for these systems, the mass ratios are generally smaller at the onset of mass transfer, and in many cases dynamical instability (followed by a CE phase) does not develop. Also, the CE phase does not often involve a HG donor, and the progenitors of BH-NS and NS-NS systems are likely to survive. Mixed systems, BH-NS, are rather rare (see O'Shaughnessy et al. 2007b), in a study that focused on deriving empirically constrained merger rates, explored a very large model parameter space; although, naturally, the BH binary merger rates are not always as low as for the two models A and B presented here, they too find that LIGO detection rates are expected to be dominated by NS-NS mergers, without, however, identifying specific evolutionary phases responsible for this effect.
also BKB02; O’Shaughnessy et al. 2007b) and are not predicted to contribute significantly to inspiral detection rates (lower by about a factor of 2 compared to BH-BH binaries in the models presented here, ~1 in 20 detections; see models A and B). In addition, the Galactic merger rates for NS-NS systems are modified, but not as significantly as the BH-BH rates. There is a decrease (by a factor of ~5) in merger rates between model A (~20 Myr^{-1}) and model C (~100 Myr^{-1}). This decrease can be attributed, in approximately even numbers, to (1) early evolution with progenitors evolving through a CE with a hydrogen-rich HG massive donor and (2) late evolution with progenitors evolving through a CE with an HG low-mass helium star donor. Phase (2) eliminates most of the previously identified ultracompact NS-NS binaries (e.g., Belczynski & Kalogera 2001), while phase (1) eliminates some of the wider classical systems. Nevertheless, the NS-NS merger rates from models A and B reported here are still consistent with the most recent empirical estimates (~3–190 Myr^{-1}; Kim et al. 2006). Provided that our understanding of CE phases with HG donors is correct, NS-NS mergers are predicted to strongly dominate the inspiral signal (~90% of inspiral events). Although the rates are too small to expect a detection at the current initial LIGO stage (~0.005 yr^{-1}), they are quite high for Advanced LIGO, with tens of detections expected every year (~20 yr^{-1}).

Mergers of compact objects, either NS-NS or BH-NS, are currently the leading progenitor model for short-hard GRBs (for a recent review, see Nakar 2007). We have recently presented a study devoted to the connection of these mergers with short-hard GRBs (Belczynski et al. 2006). In view of the decreased BH-NS rates reported here, such mergers may become less favored as potential GRB progenitors compared to NS-NS mergers. Although formation of the previously identified ultracompact NS-NS population is inhibited, if CE events with HG donors always lead to mergers, we still find that a small, but significant, fraction of NS-NS binaries have merger times shorter than ~100 Myr, and such mergers would be taking place in star-forming galaxies. We address these and other related issues in the forthcoming paper mentioned above, K. Belczynski et al. (2007, in preparation).

Our primary focus in this study has been to examine the important effect CE episodes with HG donors have on BH-BH formation and merger rates; we point out this importance by comparing a set of only three models that clearly illustrate the important physical effects relevant to this issue. Given the small number of models, however, the reported rates do not fully represent the intrinsic, quantitative uncertainties associated with rate predictions from population synthesis calculations (see, e.g., O’Shaughnessy et al. 2007b, where a broader but less specific model exploration has been presented, for a discussion of the issue of rate uncertainties).

Last, we emphasize that these estimates do not include the contribution from systems formed in dense star clusters, as we have considered only the evolution of field stars. Following the example of the Milky Way, we note that only 1 out of 5 close NS-NS systems is found in a Galactic globular cluster, and we do not expect a significant rate increase for NS-NS merger detection (Phinney 1991). However, it has been pointed out that dynamical interactions in dense stellar systems (e.g., globular clusters) can produce close BH-BH systems more effectively than in a field population (e.g., Portegies Zwart & McMillan 2000; O’Leary et al. 2006). This is an important issue, and predictions depend on the number of stars in dense clusters within reach of ground-based gravitational wave detectors, the initial conditions of these clusters, and the interplay between single and binary star evolution and dynamical processes. These issues are currently under investigation (e.g., R. M. O’Leary et al. 2007, in preparation; A. Sadowski et al. 2007, in preparation; N. Ivanova et al. 2007, in preparation), and once the results are available, they should be combined with the field merger rates for a complete description of anticipated inspiral and merger detections with LIGO.

We express special thanks to R. O’Shaughnessy for useful discussions and help with computationally demanding calculations and an anonymous referee for several useful comments. K. B. thanks the Northwestern University Theoretical Astrophysics Group for its extended, warm hospitality. We acknowledge partial support through KBN grant 1P03D022228 and 1P03D005350 (K. B. and T. B.), a Packard Foundation Fellowship in Science and Engineering, NSF grants PHY-0353111 and AST 04-49558 (V. K.), and NSF grant AST 02-00876 (R. E. T.).

7 It will be 1 out of 6, if PSR J1906+0746 is confirmed as an NS-NS binary (Lorimer et al. 2006).

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