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

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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 can 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 a new binary evolution process that can 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 always leads to a merger, preventing the double-black-hole formation. Using population synthesis calculations, we 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 20) compared to double-neutron-star binaries. Our predicted detection rates for Advanced LIGO are now much lower for double black holes (~ 2 yr^{-1}), but are still high for double neutron stars (~ 40 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 modeling of the CE phase needs 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, 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,b,c). In this work we discuss the likelihood for 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, 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 for the most recent estimates). The theoretical studies have been carried out most often via population synthesis methods, that allows 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, Postnov & Prokhorov 1997; Bethe & Brown 1998; De Donder & Vanbeveren 1998; Bloom, Sigurdsson & Pols 1999; Fryer, Woosley & Hartmann 1999; Nelemans, Yungelson & Portegies Zwart 2001) and different results were discussed in Belczynski, Kalogera & Bulik (2002a: BKB02).

After the 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 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. 2006). This model is now used to calculate the merger rates of double compact objects, and to reexamine the chances for detection of gravitational bursts from double compact object mergers. New results, in the context of gravitational waves and double compact object mergers, have been recently reported in O'Shaughnessy, Kalogera & Belczynski (2006a) and O'Shaughnessy et al. (2006b). The results of the above studies and presented here are complementary, as O'Shaughnessy et al. (2006b) predominantly conducted the search of parameter space to constrain population synthesis models, while here we discuss the specifics of evolution leading to formation of double compact objects and present new 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.

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 followed 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 such systems in dense stellar environments (see Portegies Zwart & McMillan 2000; O'Leary et al. 2006) is currently under intense investigation.

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. 2002b) and gravitational-wave inspiral sources (BKB02). In recent years `StarTrack` has undergone major updates and revisions in the physical treatment of various binary evolution phases. The new version has already been tested with respect to observations and detailed evolutionary calculations (Belczynski et al. 2006), and has been used in various applications (e.g., Belczynski & Taam 2004; Belczynski et al. 2004; Belczynski, Bulik & Ruiter 2005). The most important updates for compact object formation and evolution include: a full numerical approach to binary 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). In the helium star evolution, which is of a crucial importance for the formation of new classes of double compact objects (e.g., Ivanova et al. 2003), we have applied a conservative treatment matching closely the results of detailed evolutionary calculations. While in the mass transfer phase systems are examined for potential development of a dynamical instability, in which case the systems are evolved through a common envelope (CE) phase. We treat CE events through 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. (2006).

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., BKB02, and earlier work) we have allowed for the possibility of binary survival in case the CE was initiated by a star crossing Hertzsprung gap (HG). Once the system evolves into the CE, it was calculated whether a system emerges as a tight post-CE binary or produces a single, fast rotating star as a result of binary component merger. However, a HG star does not have a clear entropy jump at the core-envelope transition (Ivanova & Taam 2004). Therefore, once a companion starts inspiral into a HG star there is no clear boundary where the inspiral ceases and a merger is formed (see e.g., Taam & Sandquist 2000). In this case, the orbital decay timescale is expected to be shorter than the mass loss timescale. In current modeling, we assume that any CE involving a HG donor leads eventually to a binary component merger and to the formation of a single object. As many potential double compact object progenitors evolve through the CE phase (see BKB02 and their Table 3), we have recalculated double compact object populations. In particular it is found that close BH-BH systems are affected the most, as the majority of their potential progenitors evolve through CE with a HG donor.

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 of each other and to form a bound BH-BH system. Here, interest is focused only in those binaries that form BH-BH systems on very tight orbits, so the inspiral (gravitational radiation emission) timescale is shorter than 10 Gyr. Only these BH-BH systems can merge and contribute to gravitational wave detection rates (at least in a Milky Way-type of galaxy). There are number of processes that can prohibit the formation of BH-BH system. The major factors involve component merger in a close binary evolving through a mass transfer episode (single star formation), and binary disruption upon a formation of a BH due to the mass loss and potential natal kick a BH may receive. However, it is important to keep in mind that these same processes (e.g., adequately placed natal kick) allow in some circumstances the formation of close BH-BH systems. In Table 1 the major formation channels for close BH-BH binaries are illustrated. Model A is our reference model with input physics described in detail in Belczynski et al. (2006). The accretion onto compact objects in a CE phase was turned off, following the recent work that indicates that only a very small amount of mass may be accreted during a CE phase (E.Ramirez-Ruiz, private communication). Other models are altered as compared to the reference model by change of only one parameter. In model B, we allow for a full hyper-critical accretion onto compact objects (see BKB02 for the implementation). In models A and B, we do not allow binaries with a HG donor to survive a CE phase (our new standard approach). However, in model C, we allow for such a survival, and in particular this model is the closest to our previous calculations (e.g., BKB02). In models A and B BH-BH formation does not involve CE, but consists of a series of non-conservative 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 the CE episode encountered, but in this case it involves a donor that is already an evolved star (core helium burning) and not a HG star. In model C, most of BH-BH systems formed along evolutionary channels involving a CE phase, and, in most of these episodes, the donors are HG stars (BHBH:05,06). The evolutionary sequences not involving a CE with a HG donor are also found in model C, but these are very rare and they are included, among other inefficient sequences, in channel BHBH:07.

In Table 2 the Galactic merger rates for double compact objects are presented. The rates are obtained for two calibrations. First, we have calibrated our results based on the star formation rate. We have adopted a continuous star formation rate in the Galaxy of 3.5 $\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$ (O'Shaughnessy et al. 2006b) lasting for 10 Gyr. In addition, a combined rate of SN II and SN Ib/c estimated for a Milky Way type galaxy of $2 \times 10^{-2}\ \mathrm{yr}^{-1}$ is used to obtain an alternative calibration (Cappellaro, Evans & Turatto 1999 for a Galactic blue luminosity of $L_{\mathrm{B}} = 2 \times 10^{10} L_{\odot}$). The calibration obtained with the supernovae rate results in merger rates that are about 1.5 times higher than for the star formation calibration. For models A and B we find that NS-NS merger rates are $20 - 49$ Myr^{-1}, agreeing very well with the most recent observational estimates ($4 - 244$ Myr^{-1}; see Kalogera et al. 2004). In addition, they are also consistent with our previous estimates (~ 50 Myr^{-1} for a standard model in BKB02). The rates for binaries containing black holes are significantly lower; $0.07 - 0.14$ 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 predicted (~ 8 Myr^{-1} and ~ 26 Myr^{-1} for BH-NS and BH-BH systems in a standard model in BKB02). We also show the rates obtained for model in which we allow for survival in CE with HG donors, although such a survival is very unlikely (see § 2). That model is 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 the `StarTrack` code has undergone (see § 2 and also Belczynski et al. 2006). Here (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 a stark contrast to the other, more physical models (A and B). Note that the large decrease (factors of $\sim 300 - 800$) in BH-BH merger rates from model C to models A and B.

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, $\mathcal{R}_{\rm MW}$ (see Table 2), with

$$\mathcal{R}_{\rm LIGO} = \rho_{\rm gal} \frac{4\pi}{3} d_0^3 \mathcal{M}_{\rm dis} \mathcal{R}_{\rm MW} \quad (1)$$

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

$$\mathcal{M}_{\rm dis} = \left\langle (\mathcal{M}_{\rm c,dco}/\mathcal{M}_{\rm c,nsns})^{15/6} . \right\rangle \quad (2)$$

Note that we first calculate the cube of $(\mathcal{M}_{\rm c,dco}/\mathcal{M}_{\rm c,nsns})^{5/6}$ 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 BH-BH merger advanced LIGO rate, are discussed by Bulik, Belczynski & Rudak (2004). The scaling factors $\mathcal{M}_{\rm dis}$ for different groups of double compact objects are given in Table 2. The specific values for $\rho_{\rm gal}$, d_0 and $\mathcal{M}_{\rm c,nsns}$ were adopted from O'Shaughnessy et al. (2006b).

For initial LIGO we find that the rates are too small for detection in agreement with predictions in our earlier work, and now confirmed with the new models. The rates are presented per 1 yr of observations. At the moment (Nov 2006) initial LIGO has collected about 1 yr of solid data and is expected to collect an additional full yr of data. However, even for two years of observations, rates of double compact object mergers are too low for an inspiral detection. For advanced LIGO we expect quite significant detection rates. For physical models (A and B) the detection rate is dominated by NS-NS events (~ 40 yr^{-1}), with a small contribution of BH-BH inspirals (~ 2 yr^{-1}), and an even smaller contribution of BH-NS mergers (~ 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 a year; see model C), dominated by populous BH-BH mergers, as compared to new smaller rates ($\sim$ tens a year; see models A and B) obtained for models with a dominant NS-NS population.

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-BH merger rates predicted from population synthesis models of binaries in galactic fields: 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 (~ 500) than previously predicted (e.g., model C here, and BKB02). The consequence is that BH-BH merger could become only a small contributor (~ 1 in 20 detections, see models A and B; see also O'Shaughnessy et al. 2006b) to inspiral detection rates for ground based detectors like LIGO, in contrast to earlier predictions in which the BH-BH inspiral strongly dominated the detection rates.

If the understanding of 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 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 formation of BH-BH systems. Also the observed chirp mass distribution is a very sensitive function of the model of binary evolution and can lead to further constraints on other processes important for the formation of BH-BH systems (Bulik & Belczynski 2003; Bulik et al. 2004).

In our analysis we have considered only the evolution of field stars. However, it has been pointed out that dynamical interactions in dense stellar systems (e.g., globular clusters) can potentially produce close BH-BH systems more effectively than 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 the reach of ground gravitational-wave detectors, the initial conditions of these clusters, and the interplay between single and binary star evolution and dynamical processes. This issues are currently being investigated (e.g. O'Leary, O'Shaughnessy & Rasio in preparation; Sadowski et al. in preparation; Ivanova et al. in preparation), and once the results are available, they should be combined with the field merger rates, for a complete description.

Several additional calculations were performed to examine the robustness of our findings. First, we applied an alternative prescription for CE treatment (see Nelemans & Tout 2005). Second, a model was calculated in which we did not allow for CE survival in case a donor is a He star evolving through the helium HG (additionally to hydrogen HG donors; all other models). Merger rates for BH-BH binaries are virtually the same as for models A and B. In the case of binaries with a NS, the rates are smaller (by a factor of ~ 1.5), but this does not significantly affect our predictions for LIGO. We will discuss these and other evolutionary effects in a subsequent study dedicated to NS-NS mergers (Belczynski et al. 2007, in preparation).

As discussed throughout this study the decrease in merger rates is smaller for BH-NS and NS-NS binaries as compared with BH-BH systems. It 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 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 also BKB02 and O'Shaughnessy et al. 2006b) and are predicted not 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 40 detections, see models A and B). In addition, the Galactic merger rates for NS-NS systems do not change significantly. There is a small decrease (by a factor of ~ 2) in merger rates between models A and B (~ 40 Myr^{-1}) and model C (~ 80 Myr^{-1}), since some potential NS-NS progenitors evolve through the CE with a HG donor. However, the merger rates are comparable with previous results (~ 50 Myr^{-1}, BKB02) and, more importantly, they are consistent with the most recent empirical estimates ($\sim 20-300$ Myr^{-1}, Kalogera et al. 2004). Provided that the understanding of CE phases with HG donors is correct, the new qualitative result is that NS-NS mergers are predicted to strongly dominate the inspiral signal (over $\sim 90\%$ of inspiral events). Although the rates are too small to expect a detection at the current initial LIGO stage (~ 0.01 yr^{-1}), they are very high for Advanced LIGO with tens of detections expected every year (~ 40 yr^{-1} for models A and B, and ~ 90 yr^{-1} for model C). We emphasize that these estimates do not include the contribution from systems formed in dense clusters. However, following the example of Milky Way, we note that only 1 out of 5 close NS-NS systems is found in Galactic globular cluster[1]. A detailed study of new NS-NS models and comparison with the observed population is underway (Belczynski et al. 2007, in preparation).

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[1] And it is 1 out of 6, if PSR J1906+0746 is confirmed as NS-NS binary (Lorimer et al. 2006).

TABLE 1
DOUBLE BLACK HOLE FORMATION CHANNELS

Formation Channel (Model)	Relative Efficiency [a]	Evolutionary History [b]
BHBH:01 (A, B)	50 %	NC:a→b, SN:a, SN:b
BHBH:02 (A, B)	25 %	SN:a, SN:b
BHBH:03 (A, B)	13 %	SN:a, CE:b→a, SN:b
BHBH:04 (A, B)	12 %	NC:a→b, SN:a, NC:b→a, SN:b
BHBH:05 (C)	65 %	NC:a→b, SN:a, CE:b→a, SN:b
BHBH:06 (C)	28 %	NC:a→b, CE:b→a, SN:a, SN:b
BHBH:07 (C)	7 %	all other

[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): non-conservative mass transfer (NC), common envelope (CE), supernova explosion/core collapse event (SN). Arrows mark direction of mass transfer episodes.

TABLE 2
GALACTIC MERGER RATES[a] [MYR^{-1}]

Model	NS-NS	BH-NS	BH-BH	Comments
A	31-49 (0.92)[b]	0.07-0.11 (8.32)	0.02-0.03 (71.1)	reference model
B	20-31 (1.12)	0.09-0.14 (8.27)	0.01-0.02 (64.0)	full CE accretion
C	68-101 (0.95)	3.2-4.8 (7.25)	7.7-11 (50.3)	CE for HG stars

[a] Range in rates results from different calibrations used. Low rates are obtained with star formation calibration, while high with supernova calibration.

[a] In parenthesis we list distance scaling factors $\mathcal{M}_{\rm dis}$, see eq. 2.

TABLE 3
LIGO DETECTION RATES [YR^{-1}]

Model[a]	NS-NS	BH-NS	BH-BH
A,LIGO1	0.008-0.012	0.0002-0.0003	0.0004-0.0006
B,LIGO1	0.006-0.010	0.0002-0.0003	0.0003-0.0004
C,LIGO1	0.017-0.025	0.0061-0.0090	0.10-0.15
A,LIGO2	33-51	0.68-1.1	1.6-2.5
B,LIGO2	28-44	0.82-1.3	1.1-1.8
C,LIGO2	73-109	26-39	439-655

[a] Models are presented for initial LIGO (LIGO1: range of 18.4 Mpc) and advanced LIGO (LIGO2: range of 300 Mpc).