BLACK HOLE SPIN EVOLUTION: IMPLICATIONS FOR SHORT-HARD GAMMA RAY BURSTS AND GRAVITATIONAL WAVE DETECTION

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ABSTRACT

The evolution of the spin and tilt of black holes in compact black hole - neutron star and black hole - black hole binary systems is investigated via the population synthesis method. Based on recent results on accretion at super Eddington rates in slim disk models, estimates of natal kicks, and the results regarding fallback in supernova models, we obtain the black hole spin and misalignment. It is found that the spin parameter, \( a_{\text{spin}} \), is less than 0.5 for initially non rotating black holes and the tilt, \( i_{\text{tilt}} \), is less than 40\(^\circ\) for 50\% of the systems in black hole - neutron star binaries. Upon comparison with the results of black hole - neutron star merger calculations we estimate that only a small fraction (\( \sim 0.02 \)) of these systems can potentially produce a short-hard gamma ray burst. Only for high initial black hole spin parameters (\( a_{\text{spin}} > 0.6 \)) can this fraction be significant (\( \sim 0.35 \)).

1. INTRODUCTION

Double compact object binaries have attracted much attention in recent years as primary sources of gravitational wave radiation (GR) and as potential sites for the short-hard gamma ray burst (GRB) phenomenon. As such, intensive searches for the inspiral signal from double neutron stars (NS-NS), double black holes (BH-BH) and mixed black hole - neutron star (BH-NS) systems are currently underway at ground based GR observatories (e.g., LIGO or VIRGO; for recent review see Kalogera et al. 2007).

Of these systems, the mergers of NS-NS and BH-NS systems have been suggested to produce short-hard GRBs (for a recent review see Nakar 2007). However as new NS-NS binaries are discovered (e.g., Lorimer 2005), there has yet to be a detection of a BH-NS or BH-BH system.

Despite the accumulation of observational data on short-hard GRBs from the HETE-II and SWIFT satellites, the origin of these GRBs still remains elusive. Theoretical predictions of the compact merger model have been compared to observations in the hope of identifying the possible progenitor (e.g., Nakar, Gal-Yam & Fox 2005; Belczynski et al. 2006), but some specifics of the model are still lacking.

For example, to assess the validity of BH-NS merger as a short-hard GRB progenitor, it is usually assumed that all these mergers produce a GRB. However, recent hydrodynamical simulations (e.g., Setiawan, Ruffert & Janka 2004; Faber et al. 2006; Shibata & Uryu 2006; Rantsiou & Rasio 2007, in prep.) indicate that only a fraction of these binaries can potentially produce a GRB. Specifically, the existence of a thick torus of material is required such that it can be rapidly accreted onto the central BH to produce a GRB. To satisfy this constraint, the NS must be disrupted prior to its final plunge below the BH event horizon with sufficient angular momentum such that the remnant material can form an accretion torus. In this case, only compact systems with specific parameters (spin, mass ratio, and BH spin tilt with respect to the orbital angular momentum axis) can provide the requisite initial conditions for GRB production. Accordingly, we report on the results of our investigation of the spin magnitude and tilt in merging BH-NS binaries to estimate the fraction of BH-NS systems that can potentially produce short-hard GRBs.

The spin of the BH in BH-BH and BH-NS binaries is of special interest in the search for gravitational wave signatures in existing data streams from ground-based observatories. On the one hand, population synthesis studies (e.g., Fryer, Woosley & Hartmann 1999; Nelemans, Yungelson & Portegies Zwart 2001; Belczynski et al. 2007b) attempt to provide realistic merger rates and the characteristic properties of the merging binaries, while, on the other, detailed general relativistic calculations of mergers (e.g., Baker et al. 2006; Buonanno, Cook & Pretorius 2007) attempt to predict the exact shape of the GR signal.

These latter studies are essential for guiding the search for the inspiral signal that currently involves the use of a limited number of pre-calculated gravitational wave templates (e.g., Abbott et al. 2005; Abbott et al. 2006). It is well known that if the spin of a BH is significant and if it is misaligned with respect to the orbital angular momentum
axis, the shape of GR signal will differ drastically from the non-spinning/aligned case (Apostolatos et al. 1994; Kidder 1995; see also § 2.5). Yet, so far the search methods presented in the literature (e.g., Abbott et al. 2005; Abbott et al. 2006) employ non-spinning templates only.

The previous studies of BH spins in compact binaries in the context of BH-NS systems were carried out Kalogera (2000), Grandclément et al. (2004) and O’Shaughnessy et al. (2006). The spin up of the BH via binary evolutionary processes was estimated, and it was found that accretion in the common envelope (CE) phase was a major contributing factor in significantly spinning up the BHs. These early results are reassessed and extended here since (i) now only very few BH-BH progenitor systems are predicted to evolve through the CE phase (Belczynski et al. 2007b), (ii) for systems evolving through the CE phase the Bondi-Hoyle accretion mode may overestimate the accretion (and spin-up) rates (see § 2.2), and (iii) during the stable mass transfer phases the degree of spin up requires reevaluation in view of the possibility that the BH can accept mass at rates approaching ~ 100 times the critical (Eddington) accretion rate (e.g., Abramowicz et al. 1988; Ohsuga et al. 2005). Since the predictions of compact object spin misalignment depend critically on the natal kick distribution, we make use of the most recent work on natal kicks by Hobbs et al. (2005). Finally, we also extend previous studies to include the double black hole binary population.

In the next section, the various elements of our model are described. The results of our BH spin calculations are presented in § 3. Finally, in § 4 we conclude and discuss the implications of our findings.

2. MODEL

2.1. Population Synthesis Model

Binary population synthesis is used to calculate the populations of close BH-NS and BH-BH binaries that merge within 10 Gyr. The formation of double compact objects is modeled via binary evolutionary processes in the absence of stellar dynamical processes (e.g., in the cores of globular clusters). The formation of BH-BH systems in dense environments was recently studied by Portegies Zwart & McMillan (2000) and O’Leary et al. (2006). No relevant studies are available for BH-NS binaries, as their formation rate in dense environments is likely negligible, as was predicted for NS-NS systems (e.g. Phinney 1991).

Our population synthesis code, StarTrack, was initially developed to study double compact object mergers in the context of GRB progenitors (Belczynski, Bulik & Rudak 2002b) and gravitational-wave inspiral sources (Belczynski, Kalogera, & Bulik 2002a: hereinafter BKB02). In recent years StarTrack has undergone major updates and revisions in the physical treatment of various binary evolutionary phases, and especially the mass transfer phases. The new version has already been tested and calibrated against observations and detailed binary mass transfer calculations (Belczynski et al. 2007a), and has been used in various applications (e.g., Belczynski & Taam 2004; Belczynski et al. 2004; Belczynski, Bulik & Ruiter 2005; Belczynski et al. 2006; Belczynski et al. 2007b). The physics updates that are most important for compact object formation and evolution include: a full numerical approach for 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 matching closely 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 non-conservative 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). In case the CE is initiated by a star crossing the Hertzsprung gap (HG) we assume a merger and abort further binary evolution. This is due to the fact that there is no clear core-envelope boundary (and no entropy jump as for more evolved stars) in the interior structure of HG donors to facilitate the formation of a remnant binary system. As a consequence, a large decrease in the formation efficiency of close double compact binaries results (Belczynski et al. 2007b). For a detailed description of the revised code we refer the reader to Belczynski et al. (2007a).

2.2. BH Accretion Model: Spin Magnitude

The formalism of Brown et al. (2000) is adopted to describe the spin evolution of a BH as taken from the energy and angular momentum driving the killing vector of the Kerr metric (Boyer & Lindquist 1967). The Boyer-Lindquist coordinates allow for a continuous transformation across the double horizons of the Kerr metric, preserving the essential singularity at $r = 0$, and also allowing us to address the stress-energy tensor inside the BH. As such, the angular momentum is calculated for the entire mass of the BH resulting in the following evolution equations.

The BH spin parameter is defined as

$$a_{\text{spin}} = \frac{J}{M_{\text{bh}}^2 G}$$

(1)

where $M_{\text{bh}}$ denotes the BH mass, $J$ its angular momentum, and $G$ and $c$ are the gravitational constant and the speed of light, respectively. The angular momentum, $l$, and energy, $E$, of the accreted material with rest mass $M_{\text{rest}}$ can be expressed as

$$l = \frac{R_{\text{in}}^2 - R_{\text{bh}} R_{\text{in}} + a_{\text{sp}}}{R_{\text{in}}(R_{\text{in}} - 2 R_{\text{bh}} R_{\text{in}} + a_{\text{sp}} \sqrt{2 R_{\text{bh}} R_{\text{in}}})^{1/2}} \times c \sqrt{\frac{R_{\text{in}} R_{\text{bh}}}{2}} M_{\text{rest}}$$

(2)

and

$$E = \frac{R_{\text{in}}^2 - R_{\text{bh}} R_{\text{in}} + a_{\text{sp}}}{R_{\text{in}}(R_{\text{in}} - 2 R_{\text{bh}} R_{\text{in}} + a_{\text{sp}} \sqrt{2 R_{\text{bh}} R_{\text{in}}})^{1/2}} \times c^2 M_{\text{rest}}$$

(3)
where \( R_{\text{bh}} = 2GM_{\text{bh}}/c^2 \) is the Schwarzschild radius of a BH, \( a_{\text{sp}} = J/M_{\text{bh}}c = a_{\text{spin}}(GM_{\text{bh}}/c^2) \), and the last stable orbit radius is calculated from

\[
R_{\text{iso}} = \frac{R_{\text{bh}}}{2} \left\{ 3 + z_2 - \sqrt{(3-z_1)(3+z_1+2z_2)} \right\}^{1/2}
\]

with

\[
z_1 = 1 + \left[ 1 - \frac{4a_{\text{sp}}^2}{R_{\text{bh}}^2} \right]^{1/3}
\]

\[
(1 + 2a_{\text{sp}}/R_{\text{bh}})^{1/3} + \left( 1 - \frac{2a_{\text{sp}}}{R_{\text{bh}}} \right)^{1/3}
\]

\[
z_2 = \left( \frac{4a_{\text{sp}}^2}{R_{\text{bh}}^2} + z_1^2 \right)^{1/2}.
\]

The accretion of \( M_{\text{rest}} \) onto a BH changes its gravitational mass to

\[
M_{\text{bh},f} = M_{\text{bh},i} + \frac{E}{c^2}
\]

where the indices \( i, f \) correspond to the initial (pre-) and final (post-accretion) values. The accretion of \( M_{\text{rest}} \) onto a BH changes its angular momentum to

\[
J_f = J_i + l
\]

where the initial angular momentum is obtained from eq. (1)

\[
J_i = a_{\text{spin},i}M_{\text{bh},i}^2G/c
\]

and the new BH spin is calculated from

\[
a_{\text{spin},f} = \frac{J_f}{M_{\text{bh},f}^2G}.
\]

Since the BH spins at formation are unknown, we perform our calculations for a wide range of the initial values of spin parameter, including the non-spinning BH case \( a_{\text{spin},\text{init}} = 0 \) as well as rapidly rotating BH cases \( a_{\text{spin},\text{init}} > 0.9 \). We refer to case of \( a_{\text{spin},\text{init}} = 0 \) as low spin, \( a_{\text{spin},\text{init}} = 0.5 \) as moderate spin, and \( a_{\text{spin},\text{init}} = 0.9 \) as high spin.

Given the mass transfer rates obtained from the population synthesis, we make use of calculations of super-critical accretion flows around BHs to estimate the mass accretion rate (e.g., Abramowicz et al. 1988; Ohsuga et al. 2002; Ohsuga et al. 2005). Recently, Ohsuga et al. (2005) demonstrated that photon trapping in thin accretion disk models is important, allowing accretion at rates significantly exceeding the critical Eddington value \( (M_{\text{edd}}) \). In particular, for a flow rate \( \dot{M} \) (e.g., transfer rate from a donor star \( M_{\text{don}} \) of \( \sim 1000 \times M_{\text{edd}} \), matter was accreted at a rate at the level of \( \dot{M}_{\text{acc}} \sim 100 \times M_{\text{edd}} \), with the remaining matter lost in disk outflow due to strong radiation pressure effects. For smaller flow rates, the disk temperatures are lower, and hence a greater fraction of the transferred material will be accreted. Since similar detailed calculations for lower flow rates are not available, we adopt a simple prescription for the mass accretion rate onto a BH as follows

\[
\dot{M}_{\text{acc}} = \begin{cases} 
-\dot{M}_{\text{don}} & |\dot{M}_{\text{don}}| \leq 100 \times \dot{M}_{\text{edd}} \\
100 \times \dot{M}_{\text{edd}} & |\dot{M}_{\text{don}}| > 100 \times \dot{M}_{\text{edd}} 
\end{cases}
\]

In the case of a NS accretor the accretion is limited to the critical Eddington accretion rate. This prescription is adopted for the case of dynamically stable Roche lobe overflow (RLOF) and is an upper limit on accretion rate. Since most of the mass transfer in progenitors of double compact objects (e.g., BH-NS and BH-BH binaries) proceeds at the high rates governed by the thermal time scale of the donor \( (\sim 1000 \times M_{\text{edd}}) \) the upper limit estimated with eq. (10) is close to the actual value found in the detailed two dimensional radiative hydrodynamical calculations of Ohsuga et al. (2005). The transferred material that is not accreted onto compact object is ejected from the system, carrying away the specific angular momentum of the compact object. The subsequent change in the binary orbit is readily obtained (e.g., Belczynski et al. 2007a).

In the case of mass transfer proceeding on dynamical timescales, a CE phase will develop. The amount of mass accreted during this phase, denoted as \( \Delta M_{\text{acc}} \), is taken to be given by

\[
\Delta M_{\text{acc}} = \begin{cases} 
0.05 - 0.1 M_{\odot} & \text{NS accretor} \\
\dot{f}_{\text{bh}} \times \Delta M_{\text{bondi}} & \text{BH accretor} 
\end{cases}
\]

where \( \Delta M_{\text{bondi}} \) is the amount of mass accreted if accretion proceeds at the Bondi-Hoyle rate, and \( \dot{f}_{\text{bh}} = 0.5 \) is a scaling factor. Since the matter within an accretion cylinder is characterized by density and velocity gradients, accretion is not spherically symmetric. The numerical calculations of Ruffert (1999) show that the accretion rate can be significantly lower than the Bondi-Hoyle rate. We use a numerical approach, presented in Belczynski et al. (2002, see their Appendix), to estimate \( \Delta M_{\text{bondi}} \). For a NS accretor, the amount of mass accreted is chosen to mildly recycle the pulsar (e.g., Zdunik, Haensel & Gourgoulhon 2002; Jacoby et al. 2005). This particular approach results in a surprisingly good match between the observed and predicted masses of pulsars in Galactic double neutron star systems (Belczynski et al. 2007, in prep.). As only part of the donor envelope is accreted onto the compact object, the remainder is ejected at the expense of the change in orbital energy. We use the standard energy balance (e.g., Webbink 1984) in which fully efficient energy transfer from the orbit to the envelope (\( a_{\text{acc}} = 1 \)) is assumed to calculate the change of orbital separation.

An example of the spin magnitude evolution for a BH with initial mass of 10 \( M_{\odot} \) is illustrated in Figure (1). In the upper panel, we consider the BH spin evolution for three different mass accretion rates \( \dot{M}_{\text{acc}} = 1 \times, 10 \times, 100 \times M_{\text{edd}} \), where \( M_{\text{edd}} = 3.1 \times 10^{-7} M_{\odot} \) yr\(^{-1} \) is the critical Eddington accretion rate for a 10 \( M_{\odot} \) BH. For an initially non-spinning BH (i.e., \( a_{\text{spin}} = 0 \)), it is clear that a prolonged RLOF phase (\( \sim 10 - 30 \) Myr) is required to significantly spin up the BH (\( a_{\text{spin}} \gtrsim 0.9 \) if the accretion proceeds at the critical rate (\( \dot{M}_{\text{acc}} \)). If mass accretion is as high as 100 \( \times \dot{M}_{\text{acc}} \) then only a short time (\( \sim 0.1 - 0.3 \) Myr) is required to significantly increase BH spin. In the lower panel of Figure (1) we display the BH spin up as a function of accreted mass (e.g., in CE phase) for the three different initial BH spin values of \( a_{\text{spin}} = 0, 0.5, 0.9 \). It is easily seen that if the BH initial spin is small/moderate, a significant amount of mass must be accreted (\( \gtrsim 4 - 7 M_{\odot} \)) to increase the spin to high values (\( a_{\text{spin}} \gtrsim 0.9 \)).
2.3. Supernova Explosion Model: Spin Tilt

To estimate the degree of misalignment (tilt) of the BH spin axis relative to the orbital angular momentum axis of the binary system, we assume no tilt initial conditions. That is, (i) the spin axes of both stars in the binary system have spins that are parallel to the orbital angular momentum axis, (ii) once a compact object is formed in a core collapse/supernova explosion the spin direction is preserved (i.e., the BH spin preserves the same direction as the spin of collapsing star). In this case, the tilt results from the change of the orbital plane due to the natal kick the compact object receives in the core collapse/supernova explosion.

We assume that distribution of natal kicks is isotropic and the magnitude is obtained from a single Maxwellian with $\sigma = 265$ km s$^{-1}$ (Hobbs et al. 2005) modified in the following way

$$V_{\text{kick}} = (1 - f_{\text{fb}})V$$  \hspace{1cm} (12)$$

where $V$ is the kick magnitude drawn from Hobbs et al. (2005) distribution, and $f_{\text{fb}}$ is a fallback parameter, i.e., the fraction (from 0 to 1) of the stellar envelope that falls back onto the compact object. For a NS compact object, no fall back is assumed (energetic SN explosion) and full kicks are applied ($f_{\text{fb}} = 0$). On the other hand, for the most massive BHs, formed silently (no SN explosion) in a direct collapse ($f_{\text{fb}} = 1$) of a massive star to a BH, it is assumed that no natal kick is imparted. This would occur for the most massive stars (initial, zero age main sequence stars with masses $\gtrsim 40$ M$_{\odot}$; Fryer 1999; Fryer & Kalogera 2001) that form massive BHs ($M_{\text{bh}} \gtrsim 9$ M$_{\odot}$; Belczynski et al. 2007a). Lower mass BHs are formed accompanying a SN explosion, however only a fraction of the progenitor envelope is ejected and the rest is retained by the newly formed BH. In these cases the kick is decreased by an amount dependent on the expected fallback mass (for more details see Belczynski et al. 2007a).

The effect of the supernova explosion on the binary orbit is followed in the general case of eccentric orbits. In particular, we chose a random position on the orbit where the explosion takes place and use evolutionary formulas to estimate the mass of the compact object. The mass ejection is assumed to be spherical, and the expelled material is removed carrying the specific angular momentum of the exploding star. The newly formed compact object receives the natal kick, changing the direction and magnitude of its velocity around its companion star. If the resulting orbit is unbound the binary evolution is terminated and the two stars are followed as single objects. However, for a bound orbit the orbital parameters are recalculated to include the inclination of the orbit. Here, the change of the orbital inclination is equal to the change in direction of compact object spin with respect to the orbital angular momentum direction. In the case of double compact objects a progenitor system experiences two core collapse/supernova events and the respective tilts of the first and second born compact object are then given by:

$$i_{\text{tilt},1} = \Delta i_{\text{SN1}} + \Delta i_{\text{SN2}} \quad \text{first born}$$

$$i_{\text{tilt},2} = \Delta i_{\text{SN1}} + \Delta i_{\text{SN2}} \quad \text{second born}$$  \hspace{1cm} (13)$$

where $\Delta i_{\text{SN1}}$ and $\Delta i_{\text{SN2}}$ denote the relative change of the orbital inclination in a first and a second core collapse/supernova event respectively. In previous studies (Kalogera 2000; Grandclement et al. 2004; O’Shaughnessy et al. 2005) only BH-NS systems were considered and only the spin evolution of the BH was followed. It is assumed that the spin of first born compact object (BH) is aligned with orbit at the time of second core collapse/supernova event (i.e., $i_{\text{tilt},1} = \Delta i_{\text{SN2}}$). This assumption is based on the fact that a mass transfer episode that occurs between two supernova phases, will tend to align the spin of a BH with orbital angular momentum axis. Alignment for the progenitor filling its Roche lobe is subject to strong tidal interactions. For this case, it is likely that $i_{\text{tilt},2} = \Delta i_{\text{SN2}}$ for BH-NS systems and for some BH-BH binaries. We point out that this assumption may not be justified in evolutionary scenarios of BH-NS formation where only very little mass ($\lesssim 0.5$ M$_{\odot}$) is accreted onto a massive BH ($\sim 10$ M$_{\odot}$), or in the case of BH-BH formation where mass transfer does not occur between the two core collapse/supernova events (Belczynski et al. 2007b, see their Table 1, model A).

We shall discuss the effect of the above assumptions on spin tilt in the formation of double compact object binaries in the following sections.

2.4. Short-hard GRB Model

The mergers of BH-NS binaries have been proposed to give rise to short-hard GRBs. A common ingredient in such theoretical models is the requirement of a thick torus surrounding the BH. The subsequent accretion of matter in the torus releases the gravitational energy required to power the GRB. Setiawan et al.(2004) suggest that $\nu$-$\gamma$ annihilation in a low density funnel above the BH along its spin axis can deposit energy at a rate of $\sim 10^{50}$ erg s$^{-1}$, accounting for a total energy release of some $10^{50}$ erg for the case of a torus characterized by a mass $\gtrsim 0.1$ M$_{\odot}$ and a high viscosity orbiting a BH with spin $a_{\text{spin}} \sim 0.6$. Recent calculations of BH-NS mergers carried out using a general relativistic treatment by three independent groups (Shibata & Uryu 2006; Faber et al. 2006; Rantsiou & Raño 2007, in prep.) have explored the outcome of a merger event as a function of mass ratio, equation of state for the NS, and the misalignment of BH spin with respect to the orbital angular momentum axis.

For BH-NS mergers with a BH in the mass range of $\sim 3 - 4$ M$_{\odot}$, Shibata & Uryu (2006) conclude that the disruption of a NS by a low mass BH will lead to the formation of a low mass disk ($\lesssim 0.1$ M$_{\odot}$) around the BH which could potentially power a short-hard GRB. The formation of a massive disk was not found in their simulations, leading them to conclude that systems with massive disks ($\sim 1$ M$_{\odot}$) cannot be formed in BH-NS mergers with a non-rotating BH. Similar results were found by Faber et al. (2006), who employed a fully relativistic treatment in their simulations of BH-NS mergers for low mass ratio ($q = 0.1$) systems. In particular, most of the infalling NS mass is accreted promptly onto the BH, with a significant
fraction (\(\sim 25\%\)) of NS remaining bound in the form of a disk.

In contrast to these two groups, who assumed a non spinning BH, Rantsiou & Rasio (2007, in prep.) investigated the effect of the BH spin angular momentum and the BH spin misalignment for BH-NS mergers with mass ratio \(q \sim 0.1\) (i.e., for a 15 M\(_\odot\) BH). They found that both BH spin and their tilts play an important role in the outcome of the merger. Specifically, only for high BH spins (\(a_{\text{spin}} > 0.9\)) and tilts in the range of 20 – 40\(^\circ\), can the merger result in the ejection of significant fraction (up to 40\%\) of NS mass, part of which will remain bound to form a thick torus of mass \(\sim 0.1\) M\(_\odot\) around the BH.

A key issue for the outcome of a BH-NS merger is the relative position of the innermost stable circular orbit (ISCO), denoted by \(R_{\text{isco}}\), of the BH and the disruption radius (or tidal radius \(R_{\text{tid}}\)) of the inspiraling NS. Disruption must occur well outside the ISCO, for otherwise, the entire NS plunges below the event horizon of a BH, leaving no material to initiate a GRB. Therefore, a necessary condition for the production of a GRB is \(R_{\text{tid}} > R_{\text{isco}}\). However, this is not a sufficient condition, since (i) the disrupted material must form an accretion torus around BH and (ii) there must be sufficient material (\(\sim 0.01 – 0.3\) M\(_\odot\), e.g., Ruffert & Janka 1999) in the torus to power a GRB. To provide for sufficient material, \(R_{\text{tid}} \gtrsim 2 \times R_{\text{isco}}\). The high inclination orbits (\(i_{\text{tilt}} \gtrsim 40–90\(^\circ\)) are excluded since material not accreted by the BH in these mergers is ejected and not forming an accretion torus around the BH. We note that the position of the ISCO not only depends on the BH spin, but also on its tilt with respect to the orbital angular momentum vector. Furthermore, the relative position of \(R_{\text{tid}}\) and \(R_{\text{isco}}\) depends on the mass ratio of the NS to BH. Figure 2 illustrates the dependence and provides insight on the binary parameters that could allow for the formation of a disk/torus around the BH. Based on Figure 2 and the results of the available simulations (see above) for BH-NS mergers some constraints on the characteristics of BH-NS binaries can be placed on those mergers that could potentially power a short-hard GRB. Table 1 summarizes our criteria for a short-hard GRB production from BH-NS mergers.

2.5. Gravitational Inspiral Signal

The gravitational-wave signal resulting from an inspiral of a stellar mass compact object binary (BH-NS or BH-BH) can be detected by ground-based interferometric detectors, such as LIGO or VIRGO. These signals are strongly affected by the presence of non-parallel spin of the compact object with respect to the orbital angular momentum direction in the binary, mostly due to the orbital precession that is induced by the spin-orbit interaction.

In Figure 3 we present a comparison of the gravitational wave signals for spinning and non-spinning BHs. The inspiral is presented in terms of amplitude strain \(h\) (relative test mass shift) at the output of a given detector, defined by a linear combination of two independent polarization states of the gravitational wave (\(h_+\), \(h_\times\)) convolved with the interferometric antenna pattern (e.g., Apostolatos et al. 1994).

Both panels in Figure 3 show a noiseless waveform shape in the time domain, as it would be detected by one of the LIGO detectors and the VIRGO detector. The signal is detectable once the gravitational wave frequency enters the detector band at 40 Hz for LIGO or 30 Hz for VIRGO until the binary reaches the ISCO. The calculation was performed for a binary consisting of a 10 M\(_\odot\) BH and a 1.4 M\(_\odot\) NS, at a distance of 30 Mpc. For reference, the upper panel shows the signal for the non spinning case, while in the lower panel, the BH is characterized by \(a_{\text{spin}} = 0.1\) with a misalignment angle between spin and orbital angular momentum taken to be \(i_{\text{tilt}} = 35\(^\circ\)). Here, the NS is assumed to have negligible spin angular momentum. The waveforms were created in the 1.5 post Newtonian approximation for the phase and Newtonian amplitudes based on a simple precession model (Apostolatos et al. 1994) to describe the effect of spin. The conversion of the global signal to the local signal for each detector\(^2\) was performed using the network routines of the Monte-Carlo code developed by Roever, Meyer & Christensen (2006).

3. RESULTS

3.1. BH-NS Binaries

The evolution of massive binaries that eventually form BH-NS and BH-BH binary systems are followed, considering only those systems with coalescence times (orbital decay due to GR) less than 10 Gyr as potential GR or short-hard GRB sources. The updated merger rates of double compact objects have already been presented and discussed in the light of the recent input physics developments (Belczynski et al. 2007b), while a comparison of the physical properties of NS-NS binaries with the observed Galactic population and implications of NS-NS and BH-NS mergers for short-hard GRBs are presented in Belczynski et al. (2007, in prep.). Here, we discuss the potential effects of BH spin evolution on the theoretically expected rates of these phenomena.

In Table 2 we present the accretion history of double compact object progenitors. The accretion phases, taking place either during the CE or stable RLOF phase between the two core collapse/supernova events (first: SN1, and second: SN2) are listed. Only the first born compact object (in SN1) may increase its spin magnitude during one of the accretion phases, while the second born compact object is not subject to accretion and spin evolution. The binary population synthesis results show that the most frequent accretion mode for the BH-NS progenitors is though the CE phase only (\(\sim 72\%\)). Accretion via both CE and RLOF phases amounts to \(\sim 26\%\) of the cases, while accretion through RLOF only is rarely encountered (\(\sim 2\%\)).

In Figure 4 we show the amount of mass accreted onto the BH in BH-NS progenitors. Three different accretion modes, identified in Table 2 are presented separately. It is clear that the amount of accreted mass is of the order of \(\sim 0.5\) M\(_\odot\) independent of accretion history. This small amount directly reflects the limits placed on the accretion in the CE phase, and the adopted CE efficiency (\(\alpha_{\text{ce}} = 1\); see §4 for discussion of this dependence) for the progenitor stars entering the CE phase (\(\sim 15\) M\(_\odot\) core helium burning donor with \(\sim 10\) M\(_\odot\) BH). In the case for which accretion occurs during the RLOF phase, the donors are helium stars. These stars are not very massive stars (\(\sim 3 – 6\) M\(_\odot\)),

\(^2\)The detector signal that was calculated for LIGO and VIRGO depends (strongly) on the position in the sky, which was chosen randomly.
and the mass transfer rate very often proceeds on a thermal timescale that can reach $\gtrsim 1000 \times \dot{M}_{\text{Edd}}$, however, only a small fraction ($\lesssim 10\%$) of transferred material is accreted onto the BH (see eq. 10). Therefore, due to the limited mass accretion in both cases, the mass accreted onto the BH, in the formation of close BH-NS systems is not very large, thereby setting limits on the expected BH spin up in these binaries. We note that most of the systems evolve and accrete during the CE phase. Had a full Bondi-Hoyle accretion rate been adopted, the accreted mass would have increased to $\sim 1 \, \text{M}_\odot$. Such a small amount is insufficient to significantly increase the spin of a massive BH.

The distribution of final BH spins is presented in Figure 5 for the three different initial conditions: non spin ($a_{\text{spin}} = 0$), moderate spin ($a_{\text{spin}} = 0.5$) and high spin ($a_{\text{spin}} = 0.9$). It can be seen that, in all cases, BHs in BH-NS binaries increase their spins through accretion. For the initially non spinning case the average final spin is $a_{\text{spin}} \sim 0.2$, for moderate rotators $a_{\text{spin}} \sim 0.6$, while for initially rapidly rotating BHs we obtain $a_{\text{spin}} \sim 0.95$. The amount of spin up decreases with the initial value of spin, as it is more difficult to increase the spin of rapidly rotating objects. However, the robust conclusion may be reached in case of BH-NS binaries, that independent of initial conditions, it is expected that all BHs are spinning. Although accretion can only enhance the spin to a limited degree, some BHs can spin rapidly provided they were born with high spin.

The characteristic properties of close BH-NS binaries are illustrated in Figure 6. Most of the systems host massive BHs with masses $M_{\text{bh}} \sim 10 \, \text{M}_\odot$, leading to the rather extreme mass ratio in these systems ($q = M_{\text{ns}}/M_{\text{bh}} \sim 0.15$) as most of neutron stars have a mass $M_{\text{ns}} \sim 1.3 \, \text{M}_\odot$. The tilt distribution of BHs is also presented, revealing a drop off with the increasing tilt, with about $\sim 50\%$ of the systems characterized by rather low-to-moderate tilts ($i_{\text{tilt}} < 40^\circ$). Here, we have assumed that both supernovae contribute to the tilt of a BH (see eq. [10]). That is, the mass transfer phase between the occurrence of supernovae (found for all BH-NS progenitors) does not lead to alignment of the BH spin with respect to the orbital angular momentum. Had we allowed for such the alignment, the results would not change significantly: the distribution of tilts would look very similar, but with tilts shifted slightly to lower values (i.e., $\sim 50\%$ of systems with $i_{\text{tilt}} < 30^\circ$). Most of the BHs ($\sim 60\%$) in BH-NS binaries are formed directly (with no natal kick), while the majority of the remaining BHs are formed with a lower kick (see §2.3). Therefore, the first SN explosion (forming BH) does not induce a large (if any) change of orbital inclination. The tilts mostly originate from the second SN explosion, in which the NS is formed (full natal kick). Only a small percentage ($\sim 10 - 15\%$) of systems have tilts that are very small ($i_{\text{tilt}} < 5^\circ$) independent of the potential alignment between the two supernova events.

Given the results of our BH spin calculations presented in Figures 5 and 6 in combination with the GRB formation criteria listed in Table 1, the fraction ($f_{\text{grb}}$) of BH-NS mergers that can potentially produce a short-hard GRB can be estimated. This fraction is shown as a function of the initial BH spin in Figure 7. For low initial BH spins ($a_{\text{spin}} < 0.4$), only a very small fraction ($f_{\text{grb}} \sim 2\%$) of BH-NS mergers can potentially produce a GRB, while for high initial spins ($a_{\text{spin}} > 0.6$) the fraction becomes significant ($f_{\text{grb}} \sim 35\%$). The transition occurs for intermediate BH initial spins ($a_{\text{spin}} \sim 0.5$). In Table 1, we have identified the three separate GRB formation criteria for BHs in the various mass ranges and list the specific fractions of BH-NS systems that satisfy the criteria in Table 3. The fractions are presented for the three representative initial BH spins ($a_{\text{spin}} = 0.0, 0.5, 0.9$). The vast majority ($88\%$) of BHs fall within pop2 group ($M_{\text{bh}} = 7 - 11 \, \text{M}_\odot$), while only a small fraction of BHs ($11\%$) and ($1\%$) fall within pop1 and pop3, respectively (see also Fig. 6). Consider the dominating population pop2 where the majority ($68\%$) of systems also satisfy the mass ratio criterion ($0.13 < q < 0.2$). By imposing the requirement on the BH tilt ($< 40^\circ$) the fraction of potential GRB candidates is reduced to $\sim 0.34$. To determine the estimated rate for short hard GRBs, a criterion on the final BH spin must be imposed. For this last constraint, we have shown that the final spin depends sensitively on the initial BH spin (with a moderate increase from binary accretion). Since the spin must be quite large to produce a GRB ($a_{\text{spin}} > 0.6$) systems with low initial spins do not satisfy the spin criterion and no GRBs are predicted for pop2 ($f_{\text{grb}} = 0\%$). If, on the other hand moderate-to-large initial spins are assumed, the fraction can be as high as $f_{\text{grb}} = 22 - 35\%$. The fraction, $f_{\text{grb}} = 2\%$, for low initial BH spins marked in Figure 6 originate from the small number of BH-NS systems fulfilling the criteria in group pop1. Note that these criteria limit only the BH mass, mass ratio and tilt, but are independent of BH spin. The contribution from groups pop1 and pop3 are small because only a very small fraction of BH-NS systems are predicted to host low-mass BHs ($2.5 - 5 \, \text{M}_\odot$) and very few systems are formed with massive BHs ($M_{\text{bh}} > 11 \, \text{M}_\odot$), and simultaneously satisfy the mass ratio criterion ($0.09 < q < 0.12$).

### 3.2. BH-BH Binaries

Similar calculations to the BH-NS binaries were performed for the BH-BH binaries, and the accretion histories are listed for BH-BH progenitors in Table 2 as well. It is found that most ($76\%$) of these progenitors do not evolve through a CE nor a RLOF phase. A significant, but small, percentage (21\%) of the progenitor systems result in the accretion onto the BH during a CE phase. The average mass accreted onto the BH ($\sim 0.8 \, \text{M}_\odot$) is higher than for BH-NS progenitors ($\sim 0.5 \, \text{M}_\odot$) as BH-BH progenitors are more massive, and a larger mass reservoir is available during the CE phase. Only a very small percentage (3\%) of systems evolves through a phase of RLOF where accretion occurs onto the BH. The distribution of accreted masses is presented in Figure 8.
In Figure 9 the distribution of BH spins is illustrated for BH-BH binaries for several different assumptions on the initial spin. Since only the first born BH can evolve through an accretion phase, these results only apply to these BHs. Only a small fraction (0.24) evolve through the accretion phase increasing their spins, while the remaining majority and the second born BHs remain at their initial spin. For the initially non spinning case, the accreting majority and the second born BHs remain at their initial spin. Since only the first born BH can evolve for BH-BH binaries for several different assumptions on moderate and high initial spin the final BH spins attain through an accretion phase, these results only apply to BH systems due to larger (on average) accreted mass.

The physical properties of merging BH-BH binaries are shown in Figure 10. In the upper panel, the mass distribution for the first born and second born BH are displayed separately. As expected, the first born BHs, on average, are more massive since they originate from more massive binary components. Most of the BHs are massive (\( M_{\text{bh}} > 7 M_{\odot} \)), however there are a number of systems with lower mass BHs. The resulting mass ratio distribution is skewed toward comparable mass BHs, unlike for case of BH-NS systems. These distributions have already been described in Belczynski et al. (2007b) and, here, we present them for completeness. The new results are presented for tilt distribution where it is found that most of the tilts are low-to moderate (i.e., 50% of systems have tilts \( i_{\text{tilt}} < 50^\circ \), with a long tail distribution reaching rather extreme values \( i_{\text{tilt}} > 100^\circ \). In fact, the distribution of tilts is similar to that found for BH-NS systems (see Fig. 3). The tilt for BH-BH binaries arises from both SNe since few BHs (note their lower masses) are formed through direct collapse without a kick.  

3.3. Comparison to Earlier Work

The results of our study differ from the recent work of O’Shaughnessy et al. (2005), also based on the StarTrack code, and reflect the introduction of additional input physics and a different implementation of the code. In particular, O’Shaughnessy et al. (2005) find that the masses of BHs in BH-NS binaries range from 2 – 15 \( M_{\odot} \) and that the accretion of mass onto BHs can amount to as much as \( \sim 5 M_{\odot} \) (see their Fig.1). This leads to a significant increase in the BH spin independent of the initial BH spin (see their Fig.2 and 3). We note that the majority of the BHs in BH-NS binaries in O’Shaughnessy et al. (2005) are of low mass, starting as heavy NSs (\( \lesssim 2 M_{\odot} \)) that accreted sufficient mass to exceed the maximum NS mass limit (adopted to be 2 \( M_{\odot} \)). In addition, the full Bondi-Hoyle accretion onto the compact objects (both NS and BH) in the CE phase was adopted. In contrast, a higher NS mass limit (2.5 \( M_{\odot} \)) is adopted here, guided by the recent NS mass estimates (e.g., \( \sim 2.1 M_{\odot} \) pulsar mass in PSR J0751+1807, Nice et al. 2005), and only modest mass accretion takes place during the CE phase (see below). The combination of these two effects depletes O’Shaughnessy et al. (2005) BH-NS population by factors of \( \sim 4 - 5 \) leaving most systems with high mass BH (i.e., extreme mass ratios, as observed in our current study). The highest amount of accretion onto a BH in the CE phase found here is \( \sim 1 M_{\odot} \) (see Fig. 4), while it reaches \( \sim 5 M_{\odot} \) in O’Shaughnessy et al. (2005). This large difference stems from the combination of the following. Only 50% of the accretion in the CE phase is assumed, guided by the hydrodynamical simulations of Ruffert (1999) and noting that only a minimal accretion is permitted in the CE phase if one is to reproduce the observed NS mass spectrum (Belczynski et al. 2007, in prep). In addition, we have only considered a CE model with a high efficiency of envelope ejection (\( \alpha_{\text{ce}} = 1 \)), e.g., see Webbink 1984) while O’Shaughnessy et al. (2005) use an entire spectrum of efficiencies (\( \alpha_{\text{ce}} = 0 - 1 \)). It is to be noted that for typical BH-NS progenitors evolving through the CE phase, a change of the efficiency from our adopted value (\( \alpha_{\text{ce}} = 1 \)) to much smaller values of 0.1 and 0.01 leads to a factor of 2 and 4 increase in the amount of accreted mass onto the BH respectively. This is due to a fact that for smaller CE efficiencies the compact object sinks further into the donors envelope, resulting in greater accretion of mass, to supply sufficient energy for the ejection of the envelope. We note that very small CE efficiency values (\( \alpha_{\text{ce}} \sim 0.01 \)) tend to eliminate (through CE mergers) most of NS-NS progenitors, and lower the NS-NS predicted merger rates below the empirically estimated rates. Finally, O’Shaughnessy et al. (2005) allow for a wide range of input parameters (such as decreased stellar winds, or fully conservative mass transfer) that eventually lead to more massive donors at the time of the CE phase. This provides a larger mass reservoir for accretion onto the BH, however, this effect is less significant than the other two effects mentioned above.

4. Discussion

The evolution of the progenitors of close (coalescing) BH-NS and BH-BH binaries has been investigated with particular emphasis on the spin and tilt of the BH members in these systems. The results of our population synthesis have been used to estimate the fraction of BH-NS mergers that can potentially produce a short-hard GRB. It is found that close BH-NS systems form with rather massive BH (\( \sim 10 M_{\odot} \)), resulting in a mass ratios typically of the order of 0.14. Accretion onto BHs in the progenitors of close BH-NS binaries leads to a small increase in the BH spin. Thus, the final BH spin is only a weak function of binary accretion and primarily depends on its unknown initial value. The misalignment of the BH spin with respect to the direction of the binary angular momentum is found to be moderate (\( \lesssim 40^\circ \) for 50% of systems) and is mainly induced by the second SN explosion that forms the NS in the system.

By combining our results with the recent hydrodynamical calculations of BH-NS mergers, we estimate the fraction of these mergers which can potentially produce a short-hard GRB. It is found that only a very small percentage (\( \sim 2\% \)) of BH-NS mergers can produce GRB if the initial BH spins are small (\( \alpha_{\text{spin}} < 0.4 \)). This percentage increases to \( \sim 35\% \) if the initial BH spins are high (\( \alpha_{\text{spin}} > 0.6 \)). We point out that an estimate of a GRB rate originating from BH-NS mergers should take into account the reduction factor of the order of \( \sim 3 - 50 \) compared to previous estimates. Given this reduction factor to the already low BH-NS merger rate the observed short-hard GRBs are difficult to reconcile with the BH-NS merger scenario only (see Belczynski et al., in prep).

The spin evolution of BHs in close BH-BH binaries was also investigated. In this case, only a fraction (0.24) of
BHs in these systems moderately increase their spins due to an accretion phase in the binary progenitor. This small fraction is due to the fact that many BH-BH systems do not experience a mass transfer episode after the first BH is formed. As described in the previous section, all BHs in close BH-NS binaries increase their spin (even for initially non-spinning BHs all BHs end up with \(a_{\text{spin}} > 0.1\)) to significantly alter the shape of the GR inspiral signal. As illustrated in Figure 3 even a relatively small spin magnitude with a moderate tilt to the orbital angular momentum vector has a large effect on the inspiral waveform. Currently (Abbott et al. 2005; Abbott et al. 2006), non spinning templates are used in search for an inspiral signal in LIGO data streams. Grandclement et al. (2004) estimated that the loss of BH-NS inspiral detection due to use of non spinning templates cannot be greater than \(\sim 30\%\). As this estimate employed the possibility that all BHs in BH-NS binaries may have misaligned spins, this conclusion can be extended to BH-BH binaries, as only a small fraction of BHs increase their spin through accretion and the misalignment is of the similar order as for BH-NS binary systems. Although the detection of BH-NS and BH-BH binaries is not significantly affected by the use of non spinning templates, the parameter estimation for a detected system should incorporate techniques that allow for spinning and misaligned BHs. Our estimates of the BH spin can be used as a guide for the initial conditions in hydrodynamical and detailed relativistic simulations of the BH-BH and BH-NS mergers and their expected gravitational-wave signature. Also, BH spin is an important parameter required in estimation of the gravitational radiation recoil produced by the merger of two spinning black holes (see Baker et al. 2007 and references therein). Finally, we point out that the measurement of BH spin for the inspiraling BH binary, can yield a value of initial BH spin, especially for those BH-BH binaries that are mostly unaffected by accretion spin up. This may be the most direct way to infer the initial BH spin. We note, however, that BH-BH binaries are predicted to be very rare and may be difficult to observe as only \(\sim 2\) detections per year for advanced LIGO (Belczynski et al. 2007b) are expected.

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REFERENCES

Abbott, B. et al. 2006, Phys. Rev. D., 73, 062001
Boyer & Lindquist, 1967, Journal of Mathematical Physics, 8, 2
Buonanno, A., Cook, G., & Pretorius, F. 2007 (gr-qc/0610122)
Faber, J., Baumgarte, T., Shapiro, S., & Thorne, K. 1994, Phys. Rev. D., 50, 102002
Roever, C., Meyer, R., & Christensen, N. 2006, (gr-qc/0609131)
Table 1
GRB Formation Criteria

<table>
<thead>
<tr>
<th>Name</th>
<th>$M_{bh}$ [M$_\odot$]</th>
<th>$q$</th>
<th>$i_{\text{tilt}}$ [°]</th>
<th>$a_{\text{spin}}$</th>
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<tr>
<td>pop1</td>
<td>2.5-7</td>
<td>0.35-0.7</td>
<td>&lt; 90</td>
<td>&gt; 0</td>
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<td>pop2</td>
<td>7-11</td>
<td>0.13-0.2</td>
<td>&lt; 40</td>
<td>&gt; 0.6</td>
</tr>
<tr>
<td>pop3</td>
<td>11-15</td>
<td>0.09-0.12</td>
<td>&lt; 40</td>
<td>&gt; 0.9</td>
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</tbody>
</table>

*aDetailed description of criteria is given in § 2.4.*

Table 2
Accretion History for BH Binary Progenitors

<table>
<thead>
<tr>
<th>Name</th>
<th>Efficiency</th>
<th>Formation History$^a$</th>
<th>Mass Accreted$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>acc1 (BH-NS)</td>
<td>72%</td>
<td>..... SN1 CE SN2</td>
<td>0.48 M$_\odot$</td>
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<tr>
<td>acc2 (BH-NS)</td>
<td>26%</td>
<td>..... SN1 CE RLOF SN2</td>
<td>0.42 M$_\odot$</td>
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<tr>
<td>acc3 (BH-NS)</td>
<td>2%</td>
<td>..... SN1 RLOF SN2</td>
<td>0.53 M$_\odot$</td>
</tr>
<tr>
<td>acc4 (BH-BH)</td>
<td>76%</td>
<td>..... SN1 SN2</td>
<td>no accretion</td>
</tr>
<tr>
<td>acc5 (BH-BH)</td>
<td>21%</td>
<td>..... SN1 CE SN2</td>
<td>0.79 M$_\odot$</td>
</tr>
<tr>
<td>acc6 (BH-BH)</td>
<td>3%</td>
<td>..... SN1 RLOF SN2</td>
<td>0.34 M$_\odot$</td>
</tr>
</tbody>
</table>

*aThe evolutionary history after the first supernova (SN) that forms a BH is listed. Mass accretion may occur in the common envelope (CE) and/or during stable Roche lobe overflow (RLOF) phase.*

*bAverage accreted mass listed. For the full distribution see Fig. 4 and Fig. 8.*

Table 3
GRB Formation Fractions

<table>
<thead>
<tr>
<th>Criterion:</th>
<th>$M_{bh}$</th>
<th>$q$</th>
<th>$i_{\text{tilt}}$</th>
<th>$a_{\text{spin}}$</th>
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</thead>
<tbody>
<tr>
<td>$a_{\text{spin}} = 0$:</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>pop1</td>
<td>0.11</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>pop2</td>
<td>0.88</td>
<td>0.68</td>
<td>34</td>
<td>0</td>
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<td>pop3</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$a_{\text{spin}} = 0.5$:</td>
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<tr>
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<td>0.11</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>pop2</td>
<td>0.88</td>
<td>0.68</td>
<td>0.34</td>
<td>0.22</td>
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<tr>
<td>pop3</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$a_{\text{spin}} = 0.9$:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pop1</td>
<td>0.11</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>pop2</td>
<td>0.89</td>
<td>0.69</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>pop3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*aThe fraction of BH-NS mergers that satisfy the GRB criteria presented in Table 1 are listed. Imposition of the subsequent criteria (on BH mass, mass ratio, tilt and spin magnitude) reduces the total fraction.*
Fig. 1.— Spin evolution of a 10 M☉ black hole. Top panel: spin up dependence on mass accretion rate. Note that there is a need for a prolonged RLOF phase (∼ 10 – 30 Myr, the time not available for BH-NS progenitors) if accretion is limited to critical Eddington rate, while only short time (∼ 0.1 – 0.3 Myr) is needed for significant BH spin up at high accretion rates. Bottom panel: spin up dependence on amount of accreted (rest) mass. Note that a large amount of mass needs to be accreted (∼ 4 – 7 M☉) to significantly spin up a BH (a_{spin} > 0.9) if its initial spin is low to moderate.
Fig. 2.— ISCO radius dependence on BH spin tilt (with respect to orbital angular momentum) for three representative BH masses: 5 (top panel), 10 (middle) and 15 $M_\odot$ (bottom). The gray lines show the dependence for various BH spins ($a_{\text{spin}} = 0, 0.5, 0.9, 0.99$). The vertical dashed lines represent the disruption radius for a NS of 1.4 $M_\odot$ and $R_{\text{ns}} = 15$ km. Note that the disruption radius needs to be well outside ISCO radius to provide a necessary (but not sufficient) condition for a GRB.
Fig. 3.— Gravitational radiation inspiral signal \( (h - \text{GR wave strain}) \) of BH-NS binary with 10 M\( \odot \) BH and 1.4 M\( \odot \) NS at a distance of 30 Mpc. The signal was calculated for LIGO and VIRGO detectors for non-spinning case (unrealistic) and a low-spin (lower limit) case with \( a_{\text{spin}} = 0.1 \) and moderate tilt of \( i_{\text{tilt}} = 35^\circ \). Note the drastic difference in shape of the signal.
Fig. 4.— Mass accreted onto the BH during the evolutionary history leading to the formation of close BH-NS binaries. Mass can be accreted during the common envelope (CE), stable Roche lobe overflow (RLOF), or during a combination of the above modes. Note that BHs do not accrete a significant amount of mass ($\sim 0.5 \, M_\odot$) throughout their evolution. In this calculation BHs were assumed to be born with moderate initial spin ($a_{\text{spin}} = 0.5$).
Fig. 5.— Distribution of BH spins in close BH-NS binaries. Each calculation was performed with a different initial BH spin. Note that even for the case of initially non spinning BHs, there is a small but significant ($a_{\text{spin,init}} \geq 0.1$) increase of BH spin due to binary accretion (top panel). However, high spins ($a_{\text{spin}} \geq 0.9$) can be obtained only if BHs are initially formed with high spins (bottom panel).
Fig. 6.— Distribution of BH mass, mass ratio and tilt of BH spin in close BH-NS binaries for a model with the moderate initial BH spin ($a_{\text{spin}} = 0.5$). Note that the high masses of BHs result in an extreme mass ratio distribution and that moderate tilts dominate ($i_{\text{tilt}} < 40^\circ$ for $\sim 50\%$ of systems).
Fig. 7.— Fraction of BH-NS mergers that can produce a short-hard GRB according to the criteria presented in § 2.4. Note the strong dependence on the assumed initial BH spin; only a very small fraction (∼2%) of the mergers can produce GRB for low initial spins, while significant fraction (∼35%) is found for high initial BH spins.
Fig. 8.— Mass accreted onto BHs during the evolutionary history leading to formation of close BH-BH binaries for a model in which BHs were assumed to be born with a moderate initial spin \((a_{\text{spin}} = 0.5)\). Mass can be accreted either during the common envelope (CE), or stable Roche lobe overflow (RLOF) phase.
Fig. 9.— Distribution of BH spins in close BH-BH binaries for models characterized by an initial spin given as $a_{\text{spin, init}} = 0.0$, $0.5$ and $0.9$ for the upper, middle and lower panel respectively.
Fig. 10.— Distribution of BH mass (upper panel), mass ratio (middle panel), and tilt of BH spin (lower panel) in close BH-BH binaries for a model with a moderate initial BH spin ($a_{\text{spin}} = 0.5$). The mass distribution of the first born BH and the second born BH are shown separately.