arXiv:1312.5924v2 [astro-ph.HE] 26 May 2014

BLACK HOLE X-RAY TRANSIENTS: THE FORMATION PUZZLE

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Draft version November 12, 2018

ABSTRACT

There are 19 confirmed BH binaries in the Galaxy. 16 of them are X-ray transients hosting a $\sim 5-15\,M_\odot$ black hole (BH) and a Roche lobe overflowing low-mass companion. Companion masses are found mostly in $0.1-1\,M_\odot$ mass range with peak at $0.6\,M_\odot$. The formation of these systems is believed to involve a common envelope phase, initiated by a BH progenitor, expected to be a massive star $> 20\,M_\odot$. It was realized that it may be very problematic for a low-mass companion to eject a massive envelope of the black hole progenitor. It invoked suggestions that an intermediate-mass companion ejects the envelope, and then is shredded by the Roche lobe overflow to its current low-mass. But this creates another issue; a temperature mismatch between hot models and the observed cool low-mass donors. Finally, the main driver of Roche lobe overflow that is believed to be magnetic braking does not seem to follow any theoretically calculated models. Number of ideas were put forward to explain various parts of this conundrum; pre-main sequence donor nature, alternative approach to magnetic braking and common envelope energy was revisited. We test various proposals and models to show that no overall solution exists so far. We argue that common envelope physics is not crucial in the understanding of Galactic BH transients. Our failure most likely indicates that either the current evolutionary models for low-mass stars and magnetic braking are not realistic or that the intrinsic population of BH transients is quite different from the observed one.

Subject headings: binaries: close — stars: evolution — X-rays: binaries

1. INTRODUCTION

Nearly all confirmed Galactic BHs reside in X-ray Transient systems (BHXRTs). These are close interacting binaries comprising a BH and a low mass companion. Companions are mostly main sequence stars with a few exceptions of evolved stars (see Table 1). In this work we adopt the terminology where the star which is heavier on Zero Age Main Sequence (ZAMS) and therefore is the one to form the compact object is called a primary, whereas the other star is called a secondary.

Roche lobe overflow mass transfer leads to the formation of accretion disk around black hole (e.g., Shakura & Sunyaev (1973)), which is the source of X-ray radiation. BHXRTs spend most of the time in the so-called quiescent state when the X-ray emission is negligible in comparison to the optical emission of the secondary. The distinctive feature are X-ray outbursts with the brightness increase of a few ($\sim 3-5$) orders of magnitude. During the outbursts X-ray luminosity significantly exceeds optical luminosity ($L_x/L_{opt} \gg 1$). In few systems the recurrences have been observed (e.g., McClintock & Remillard (2006)). Disk instability connected to ionization of hydrogen atoms is claimed to be responsible for the outbursts (e.g., King et al. (1996), Dubus et al. (1999), Lasota (2001)). It is expected that transient behavior appears only for very low mass transfer rates. This naturally agrees with the low mass companions in the observed population. Alternatively, it was proposed that two-partial accretion disk is responsible for transient behaviour Menou et al. (1999). The inner Advection Dominated Accretion Flow (ADAF) part is responsible for the emission in quiescence, whereas the outer thin disk part may be, under some conditions, unstable and, therefore, responsible for the outbursts.

Black holes are predicted to form from massive stars (>

$20-40\,M_\odot$, e.g., Fryer et al. (2012)). Since massive stars have large radii ($> 10-20\,R_\odot$, e.g., Hurley et al. (2000)), initial binary orbits need to have rather large separations. Intensive wind mass loss (e.g., Vink (2013)) from a massive star may lead to a significant increase of the binary orbit. One may expect a typical orbital separation to be rather large ($\gtrsim 100\,R_\odot$) during the early evolution leading to the formation of BHXRT. Since the observed BHXRTs are Roche lobe overflow binaries with low mass companions (typically small radii), the orbital separations of the observed systems are rather small ($\lesssim 10\,R_\odot$). There must exist a process that leads to the significant orbital decay of the BHXRT progenitor. All Galactic BHXRTs are found in the isolated environment (in the Galactic field) with no apparent nearby dense clusters or any extra stellar components. In isolation, common envelope (CE) phase (Paczynski 1976) is the best known mechanism for decreasing the orbit and the formation of close and interacting binaries.

The evolution leading to the formation of BHXRT may start with the detached binary of rather extreme mass ratio. The massive star evolves off main sequence, increases its radius and initiates the Roche lobe overflow. The mass transfer proceeds on dynamical timescale and leads to the formation of CE (i.e., primary envelope engulfs entire binary system). After CE, a massive and compact core of the primary emerges on a close orbit with the unaffected companion. The primary core rapidly evolves towards core collapse and the BH formation. At this stage the orbital separation needs to be so small that evolutionary expansion of a companion and/or combined action of magnetic braking, tides and emission of gravitational radiation from the system allows for the Roche lobe overflow. Companion may start at arbitrary mass and then become low mass star by mass loss during the Roche lobe overflow phase. The mass transfer from low mass companion to a BH proceeds at the very low rate leading to the disk instability and transient behavior.

There is a number of issues with this picture. As noted early on by number of authors (Podsiadlowski et al. (1995);

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Portegies Zwart et al. (1997); Kalogera (1999)) and then later supported by more recent studies (e.g., Podsiadlowski et al. (2003); Kiel & Hurley (2006); Yungelson & Lasota (2008)) it was recognized that survival of common envelope phase is rather challenging energetically. Ejection of massive envelope of a BH progenitor by a low-mass star proves rather difficult if not impossible. This issue is approached with extra sources of energy (other than orbital) that may help unbind the massive envelope. It usually translates to invoke very high CE ejection efficiencies.

For example Yungelson & Lasota (2008) have found a need for $\alpha = 10$-40, and have justified such high values with similar findings in other evolutionary studies. It needs to be noted that their findings were obtained with rather high wind mass loss rates for O stars as compared with the most updated theoretical predictions (Vink et al. (2001); although see Eldridge et al. (2008)). High wind mass loss helps to remove part of the envelope before CE is encountered. Therefore, the already very high α values found by Yungelson & Lasota (2008) would increase if reduced wind mass loss rates were applied.

Podsiadlowski et al. (2010) speculated that possibly hydrogen-rich material from the inspiraling low-mass main sequence star can be injected into the helium-burning shell of the evolved BH progenitor. In fact, if nuclear energy can help eject the envelope it appears that $1-3\,\mathrm{M_\odot}$ donors can easily survive CE and form close systems with BHs. However, the subsequent evolution through RLOF and transient phase (as we will show in our study) will lead to the depletion of systems with mass ($\sim 0.6\,\mathrm{M_\odot}$) where most observed Galactic transients are found and will favor systems with higher mass ($\sim 1\,\mathrm{M_\odot}$). However, the proposed scenario for the efficient CE ejection may eliminate any potential issue with the low number of predicted systems in future modeling.

Ivanova & Chaichenets (2011) provided a refined binding energy estimates. Based on considerations of envelope internal behavior and energy they argued that the binding energy is about factor of $\sim 2-5$ smaller than usually estimated and suggested that this may help to form close BH systems with low mass companions. As we will show in our calculations this helps to increase the number of Galactic BH transients, however the donor mass distribution peaks at $\sim 1\,\mathrm{M_\odot}$ rather than at observed $\sim 0.6\,\mathrm{M_\odot}$.

Justham et al. (2006) argued for another line of approach to this issue with a proposal that it is intermediate-mass companions that eject the common envelope. It was proposed that later in the evolution these companions are mass depleted by the RLOF onto a BH and they become low mass stars. However, this created another problematic issue. Such stripped stars would be hotter than low-mass stars observed in the Galactic BH transients.

As Justham et al. (2006) proposed magnetic braking for intermediate-mass donors (namely magnetic Ap and Bp stars) to be a major angular momentum loss mechanism driving system evolution, Chen & Li (2006) proposed a different way of angular momentum loss from intermediate-mass stars. During the RLOF some of the matter lost from the donor may not reach the primary but form a circumbinary (CB) disk. This can potentially be the source of tidal torques, which may result in the effective angular momentum drain. However, this proposal also suffers from the temperature mismatch problem.

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[4] Actually, these authors list only $\alpha \times \lambda = 0.5$-$2$. We have used recent estimates of binding energy for massive BH progenitors ($\lambda = 0.05$; Xu & Li (2010a)) to estimate their α. Definitions of α and λ are given in Section 2.2

Ivanova (2006) delivered a potential solution of this issue. It was proposed that it is pre-main sequence stars donors feeding BHs in the Galactic transients. Pre-main sequence donors could have an intermediate-mass, but because they are cooler than main sequence stars, the temperature issue would be avoided. However, none of the Galactic BH transients are associated with or found nearby star-forming regions.

Finally, Yungelson et al. (2006) and Yungelson & Lasota (2008) pointed out that only the models with reduced or no magnetic braking for the evolution through BH transient phase (during ongoing RLOF) seem to be encouragingly close to observations. Unfortunately, recent observations of orbital decay in BH transients seem to indicate very high magnetic braking rate (González Hernández et al. 2014). Despite these observations we have tested this idea, to show that it produces an extra evolutionary problem.

The population of known X-ray binaries have a significant impact on our understanding of evolution of both high-mass and low-mass stars. For example, the NS and BH mass spectrum, with the characteristic lack of compact objects within mass range 2–5 $\mathrm{M_\odot}$ can be qualitatively explained with the specific model of supernova explosion (Belczynski et al. 2012b) or it may be an observational bias in BH mass measurements (Kreidberg et al. 2012). The companion mass spectrum of Galactic BHXRTs still awaits to be explained. The companion mass distribution peaks at $0.6\,\mathrm{M_\odot}$ and majority companions are found with mass below $1\,\mathrm{M_\odot}$ (see Table 1. As pointed out above it seems rather difficult to explain the existence of such systems with the standard evolutionary scenarios. We reexamine this issue to show that *(i)* common envelope is not a crucial issue in the formation of BH transients as we can produce them without invoking unrealistically high common envelope efficiencies, *(ii)* magnetic braking efficiency plays a crucial role in shaping the donor mass distribution and that *(iii)* we cannot reproduce the observed population in any of our simulations.

In the next section ($\S$2) we briefly describe our population synthesis code `StarTrack` and several CE models are presented. In the following section ($\S$3) we discuss our predicted companion mass distributions and compare them with observations. Next section ($\S$4) contains discussion of selection effects on the X-ray binary population. Finally, our conclusions are presented in the last part ($\S$5).

2. MODELING

2.1. *Population synthesis model*

We have made use of the `StarTrack` population synthesis code. It was created with particular attention put on the evolution of massive stars, as they can produce neutron stars (NS) and BHs. The single stellar models were adopted from Hurley et al. (2000), who focused mostly on evolution of low mass stars and white dwarf formation. A thorough description of the code may be found at Belczynski et al. (2002) and Belczynski et al. (2008).

Evolution leading to the formation of BH transients involves two distinctive phases: CE inspiral and BH formation. The approach to CE is described in the following subsections, here we give brief description of BH formation. We use a core collapse/supernova model that is based on neutrino supported convective explosion engine with rapid explosion development (Fryer et al. 2012). This model results, with qualitatively reasonable compact object mass spectrum. Most NSs are found with mass ~ 1.3–$1.4\,\mathrm{M_\odot}$ but with a long tail ex-

tending to over $2\,\mathrm{M}_\odot$. Galactic BHs (solar metallicity models) are found with mass in range $5\text{–}15\,\mathrm{M}_\odot$. Note that this reproduces the observed mass gap between NSs and BHs (Belczynski et al. (2012a); although see Kreidberg et al. (2012)). For NSs we adopt high natal kicks during supernova explosion derived from observations of pulsar velocities in Galaxy; the Maxwellian distribution of kicks with $\sigma = 265\,\mathrm{km\ s^{-1}}$ (Hobbs et al. 2005). For BHs we use the same distribution but with lowered σ, as significant fraction of the mass ejected during SN explosion may falls back onto the BH. As a result, natal kicks for our BHs are small or negligible. This is representative for kicks originating from asymmetries in mass ejection during SNa explosion. It seems that our model is consistent with majority of BH natal kick estimates (Belczynski et al. 2012a).

For massive primaries we have adopted a steep initial mass function with power-law exponent of -2.7 (Kroupa et al. 1993). We have chosen the primary mass in range $6\text{–}150\,\mathrm{M}_\odot$ because less-massive stars are not able to evolve into a BH. Typically, in our single stellar models only stars with ZAMS mass greater than $20\,\mathrm{M}_\odot$ may form BHs. However, much lower mass limit was adopted as binary interactions (e.g., mass transfer) may effectively lower this BH threshold formation mass. The secondary mass has been taken from a wider distribution $0.08\text{–}150\,\mathrm{M}_\odot$ in such a way that the ratio of secondary to primary mass on ZAMS has a uniform distribution and is always smaller than 1 (Kobulnicky et al. 2006). The distributions of initial separations (a) and eccentricities (e) are proportional to $1/a$ (Abt 1983) and e (Duquennoy & Mayor 1991) respectively. Separations were limited to be greater than two times the sum of stars radii as to allow the formation of a binary in the first place and smaller than $10^5\,\mathrm{R}_\odot$. Whereas eccentricity is in range from 0 to 1. We have assumed binarity of 50% (2/3 stars in binaries). Such parameters are consistent with the observed Galactic binary population.

Recently, Sana et al. (2012) and Sana et al. (2013) have obtained moderately different initial distribution for massive O-type stars. In particular, it was found that there are somewhat more close binaries than implied by flat (in logarithm) separation distribution, also the binarity was found at higher level $\sim 70\%$ and it was concluded that massive O binaries are less eccentric than what we have adopted (i.e., they follow distribution $\propto e^{-0.42\pm0.17}$). It is not at all clear that these results are applicable for the progenitors of BH transients; binaries with O star and K-M dwarf as the lowest mass object in the Sana et al. (2012) observational sample was a $16\,\mathrm{M}_\odot$ star. If these distributions were applied across entire binary mass range we would expect a moderate increase in a number of BH transients.

We have evolved 2×10^7 binaries starting from ZAMS. We adopt a 10 Gyr time limit for the evolution of our synthetic binaries, which corresponds to the age of Galactic disk. We have also assumed that the star formation in the disk was constant throughout the last 10 Gyr. For each binary we note the time and duration of an X-ray transient phase with BH accretor (if encountered). Then we estimate the probability of finding a given binary in this phase at the current time. This way we can study physical properties of synthetic BHXRTs and compare them with the observed population.

In the following subsections we describe in detail how we treat and test various physical processes that may play an important role in the formation and subsequent evolution of BHXRTs.

2.2. *Standard energy CE model*

The orbital energy in a binary system can be expressed with the formula $E_{orb} = -\frac{Gm_1m_2}{2a}$ where G is the gravitational constant, m_1 and m_2 are star masses, and a is the average distance between the stars (separation). The loss of binary energy can be calculated as the difference between its energy before and after the CE phase.

$$\Delta E = E_{pre} - E_{post} = -\frac{Gm_{1,pre}m_2}{2a_{pre}} + \frac{Gm_{1,post}m_2}{2a_{post}},$$

where $m_{1,pre}$ and $m_{1,post}$ are the masses of primary star before and after losing its envelope, respectively. Similarly, a_{pre} and a_{post} are separations before and after the CE. We assume here that the mass of the low mass main sequence companion remains unchanged (no significant accretion).

The energy needed to unbind the envelope from the system is the combination of its internal energy and potential energy, but for the use of population synthesis code it is usually simplified to

$$E_{bind} = \frac{Gm_{1,pre}m_{1,env}}{\lambda R_{1,rl}} \qquad (1)$$

where $m_{1,env} = m_{1,pre} - m_{1,post}$ is the mass of the envelope, $R_{1,rl}$ is the Roche lobe radius of the primary star, and λ is a parameter describing the binding energy of the envelope (de Kool 1990). We use physical estimates of λ for stars of different size, mass and evolutionary state as calculated by Xu & Li (2010b). In this calculation the binding energy was estimated based either on gravitational energy only, or it was decreased by its internal energy. Here we use the average of the two. The typical values for BH progenitors are of the order $\lambda = 0.05$, and they do not ever rise significantly above $\lambda = 0.2$ (Dominik et al. 2012).

It is noted that the binding energy scaling was systematically studied by other groups (Dewi & Tauris (2001), Northwestern). In particular, Dewi & Tauris (2001) noted that for stars with $M \leq 20\,\mathrm{M}_\odot$ (e.g., NS progenitors) the λ may vary by large factors (almost 2 orders of magnitude) depending on the adopted core definition. They quoted values in range $\lambda = 0.05\text{–}3.5$ for their highest mass model, a $20\,\mathrm{M}_\odot$ star. Note that for our BH progenitors we use the lowest of their value, increasing binding energy and making CE ejection vary hard. Especially for systems with low mass companions. In other words we are providing a conservative approach to the CE survival and BH transient formation. Recently, it was demonstrated that for more massive stars (e.g., BH progenitors) the core definition does not change significantly the envelope binding energy (Wong et al. 2013).

The energy transfer from the orbit to the envelope may not be ideal so the parameter α was introduced. It describes what fraction of the binary orbital energy is effectively used for unbinding the envelope. We adopt $\alpha = 1$ as to allow for the easiest possible envelope ejection by a low mass star. The final equation on energy transfer can be written as

$$\alpha \left\{ \frac{Gm_{1,post}m_2}{2a_{post}} - \frac{Gm_{1,pre}m_2}{2a_{pre}} \right\} = \frac{Gm_{1,pre}m_{1,env}}{\lambda R_{1,rl}} \qquad (2)$$

This readily provides an estimate of the a_{post} from the parameters before the CE phase as the $m_{1,post}$ is assumed to be equal the core mass of the donor, which is given by evolutionary models (Hurley et al. 2000) employed in the `StarTrack` code.

The above energy balance provides only simplified picture of CE as introduced early on by Webbink (1984) and its short-comings were recently discussed by Ivanova et al. (2013). We will use it as our reference model to *(i)* test whether any improvement was achieved with recent population synthesis updates since original work of Podsiadlowski et al. (2003), and to *(ii)* contrast its predictions with other available models that we test in this study.

2.3. *Enthalpy CE model*

Ivanova & Chaichenets (2011) proposed a modified approach to the standard energy CE model. They come up with a conclusion that the sum of gravitational and thermal energies may not be the correct value for binding energy. Showing that even positive total energy could describe a stable system, they suggested to use enthalpy instead of energy as a fundamental parameter. They base their idea on the fact that transfer of the energy from companion to envelope will lead not only to the rise of the thermal kinetic energy of the gas but also to the expansion of the envelope. This expansion will result in work done by envelope. As a result we may expect that a smaller energy will be needed to unbind the envelope. This concept can be incorporated into our calculations by appropriate multiplication factor (f_λ) to the λ value in Equation 1. Ivanova & Chaichenets (2011) estimated it in the range $f_\lambda = 2 \div 5$.

We have checked the impact of this approach on BHXRT companion mass distribution for the most extreme case, $f_\lambda = 5$, that allows for the easiest ejection of the envelope. In principle, it is expected that typically companions of a lower mass will be found in this model as compared with standard energy model.

2.4. *Angular momentum CE model*

This CE model incorporates the angular momentum balance. The idea was first introduced by Paczyński & Ziółkowski (1967), and recently employed by Nelemans et al. (2000) in population synthesis studies. A linear loss of angular momentum with matter ejected from binary during the CE phase leads to

$$\gamma = \frac{\Delta J}{J} / \frac{\Delta M}{M}$$

where γ represents a constant ratio of angular momentum J loss to mass loss M, both referring to the entire binary. This can be translated into the final separation after CE in the form

$$a_f = a_i \left(\frac{m_{1,pre} m_{2,pre}}{m_{1,post} m_{2,post}} \right)^2 \frac{M_{post}}{M_{pre}} \left(1 - \gamma \frac{M_{pre} - M_{post}}{M_{pre}} \right)^2,$$

where $M_{post} = m_{1,post} + m_{2,post}$ and $M_{pre} = m_{1,pre} + m_{2,pre}$ are the total masses of the system after and before the CE phase. In this model, as in previous ones, we assume that the entire envelope is being expelled from the binary, leading either to a formation of a close system or merger of both interacting binary components.

For comparison we list below calculated final separation for the three employed CE models obtained for the exactly same system entering the CE phase. At the beginning of CE phase we have a core Helium burning star with mass $23.4 \, M_\odot$ (with He core of $15 \, M_\odot$) and a $3.6 \, M_\odot$ main sequence companion on the circular orbit with separation $a = 4000 \, R_\odot$. After CE we obtain separation $15 \, R_\odot$ (energy balance), $73 \, R_\odot$ (enthalpy) and $1921 \, R_\odot$ (angular momentum).

2.5. *Enhanced mass transfer model*

Additionally, we have checked the idea of enhancing the mass loss from the secondary due to illumination of the Roche lobe filling stellar envelope by the high energy radiation. This radiation is produced in the accretion disk around the BH and is radiated in all directions. Some part of it will, therefor, be captured by the secondary's envelope. The illuminated envelope may increase its temperature and size and this in turn may potentially lead to the increased mass transfer rate.

The exact calculation of envelope response to illumination is beyond the scope of this paper. Instead, we adopt an increase factor f_{ill} to the mass transfer rate from low mass companion to a BH. The mass transfer is first obtained for single stellar models of Hurley et al. (2000) by calculation of a star and its Roche lobe response to the mass loss with inclusion of magnetic braking (Belczynski et al. 2008). Then to mimic a potential mass loss increase we multiply it by several values of $f_{\mathrm{ill}} = 2, 5, 10$.

Since the past, and as we will see the current models, are generating typically companions of too high mass in BHXRTs, the expectation is that illumination will help to bring models to match the observations.

2.6. *Low maximum NS mass model*

In our calculations we have adopted the maximum NS mass at the value $M_{max,NS} = 3 \, M_\odot$. Here, we let this limiting value to decrease down to $M_{max,NS} = 2 \, M_\odot$. This may have an important effect on BHXRT populations as there is a possibility that a BH in a close binary system may form via accretion induced collapse (AIC) of a NS. The lower the maximum NS mass the easier it is to form BHs via AIC. Observationally, the adopted here low value is consistent with the two most massive known NSs (1.97 ± 0.04 (Demorest et al. 2010), 2.01 ± 0.04 (Antoniadis et al. 2013)). Theoretical calculations give maximum NS mass in the range 2.0–$3.2 \, M_\odot$ (e.g., Haensel et al. (2007), Chamel et al. (2013) and Kiziltan et al. (2013)).

As we can see from Table 1, the lowest mass BHs are above $\sim 5 \, M_\odot$, although the mass estimates may be observationally overestimated (see Cantrell et al. (2010) for a discussion of how past work has been flawed and how such problems may be fixed in the future; see also (Kreidberg et al. 2012) for a discussion of how this effect impacts BH populations on the whole).

3. RESULTS

In this section we test various models, assumptions and proposals from the literature that were put forward as potentially important in the formation and evolution of BH transients.

We consider only binaries with companions less massive than $2 \, M_\odot$. In Table 1 we list Galactic BH binaries. The most known BH transients have companion masses below $2 \, M_\odot$. This agrees well with the theoretical predictions that require low mass transfer rates and thus low mass donors for transient behavior to appear (e.g., Dubus et al. (1999), Menou et al. (2002)).

There are two exceptions found in our table: XTE J1819-254 and 4U1543-47. The XTE system has reported companion mass $5.5 - 8.1 \, M_\odot$. However, it appears that the companion is enriched with CNO burning products and this leads to the increased mass transfer rates allowed for the transient behavior (e.g., Dubus et al. (1999)). Furthermore, the system's outbursts do not appear like the outbursts of the other X-ray binaries – instead, they have been dramatically shorter, and

dramatically brighter than those of other X-ray transients (see e.g. Hjellming et al. (2000)). In our analysis we consider only binaries with H-rich envelopes and typical solar-like composition. This system is beyond the scope of our study. The 4U 1543-47 binary is close to our imposed limit with companion mass estimated to be in range $2.3 \div 2.6$. However, the mass estimate is a subject to several uncertainties. Orosz et al. (1998) discussed the possibility that the A2V star may not be the part of XRB and be either the background star or the outer part of the triple system. Despite the fact that comparison of mass transfer rate for such massive donors allows for the transient behavior we limit our study to stars below $2\,M_\odot$. Note that in each model we find a small number of transients with masses above $2\,M_\odot$. Inclusion of this one particular system in our analysis would not change any of our conclusions.

3.1. *CE survival with low mass companions*

We note that even stars as low as $0.5-1\,M_\odot$ may successfully eject an envelope of a very massive stars (i.e., BH progenitor; $M_{\rm zams} = 20$–$150\,M_\odot$). And this result is obtained for very restrictive values of λ that we have applied in our calculations. For massive stars with $M_{\rm zams} < 75\,M_\odot$ we employ $\lambda = 0.05$, while for higher mass stars $\lambda = 0.4$ (Xu & Li 2010a). It means that for a typical BH progenitor with $M_{\rm zams} = 30-40\,M_\odot$ we multiply binding energy by factor of $20\,(1/\lambda)$ making the envelope very hard to be ejected.

There are two ways (or their combination) to overcome the ejection problem. First, if CE is initiated on a very large orbit then there is a lot of orbital contraction available (i.e., orbital energy reservoir is large) for successful ejection of massive envelope even by low mass stars. Second, if CE is initiated late in terms of evolution of massive star it means that massive star lost most of its envelope in stellar winds. That means that not much orbital energy is required and successful envelope ejection may be achieved with low mass star. Below we give two examples of such ejections.

The binary starts with $100\,M_\odot + 1\,M_\odot$ components. At the time of CE onset the primary has just begun core He-burning ($\sim 1-2\%$ into this phase that lasts about 0.25 Myr for this star). At this time its mass was decreased by winds down to $60\,M_\odot$, with $25\,M_\odot$ He-rich core and massive $35\,M_\odot$ H-rich envelope. Pre-CE orbital separation is $a = 4000$–$5000\,R_\odot$ and star radius is $\sim 3000\,R_\odot$. After energy balance application with CE efficiency $\alpha = 1$ and binding energy scaling of $\lambda = 0.4$ (see Equation 2) the post-CE separation is $5-10\,R_\odot$; wide enough to accommodate $25\,M_\odot$ WR star and its $1\,M_\odot$ companion, and close enough to allow for onset of RLOF from the low mass star within the Hubble time.

The binary starts with $30\,M_\odot + 0.5\,M_\odot$ components. At the time of CE onset the primary is just about to finish core He-burning ($\sim 80\%$ into this phase that lasts about 0.5 Myr for this star). At this time its mass was decreased by winds down to $13\,M_\odot$, with $10\,M_\odot$ He-rich core and low mass $3\,M_\odot$ H-rich envelope. Pre-CE orbital separation is $a = 2000$–$3000\,R_\odot$ and star radius is $\sim 1500\,R_\odot$. After energy balance application with CE efficiency $\alpha = 1$ and binding energy scaling of $\lambda = 0.05$ (see Equation 2) the post-CE separation is $\sim 5\,R_\odot$; wide enough to accommodate $10\,M_\odot$ WR star and its $0.5\,M_\odot$ companion, and close enough to allow for onset of RLOF from the low mass star within the Hubble time.

3.2. *Standard model*

Figure 1 shows the predicted mass distribution for companion stars in Galactic BHXRTs. The distribution covers a broad range of masses, with significant numbers of stars in a mass range $0.1-2\,M_\odot$. There is a clear peak in the distribution at $\sim 1\,M_\odot$, and a smaller one at $\sim 0.2\,M_\odot$. The predicted distribution is quite different from the observed one that has a peak at $\sim 0.6\,M_\odot$.

Binaries responsible for the main peak of the predicted distribution consist of a rather massive primary $\sim 30-40\,M_\odot$ and a low mass secondary $\sim 1-1.2\,M_\odot$. Rapid evolution of primary leads to the Roche lobe overflow while it is core He burning. After significant orbital decay ($a = 3000\,R_\odot$; energy balance; $a = 6\,R_\odot$), the close binary emerges out of CE. Massive He core collapses to form a $\sim 7-10\,M_\odot$ BH at about 6 Myr since ZAMS. For such a massive star we assume the direct BH formation with no (or weak) supernova explosion and the orbit remains very close $a \approx 8\,R_\odot$ (no or small natal kick). Nuclear evolution on main sequence increases the radius of secondary. At the same time magnetic braking (MB) and gravitational radiation (GR) keep decreasing orbital separation over next 4 Gyr until secondary fills its Roche lobe at $a \approx 5\,R_\odot$. The secondary initiates stable Roche lobe overflow (X-ray phase begins) during its main sequence evolution at the low mass transfer rate ($\dot{M} \approx 8 \times 10^{-11}\,M_\odot\,{\rm yr}^{-1}$). At such a low mass transfer rate the system is a subject to disk instability and becomes a transient for several Gyrs. For this particular binary configuration the critical mass transfer-rate below which the system shows transient behavior is $\dot{M}_{\rm disk} \approx 10^{-10}\,M_\odot\,{\rm yr}^{-1}$ (Dubus et al. 1999). Due to such slow mass transfer rate, donor mass changes very slowly. It means that there is a high probability for the system to be discovered with secondary close to its initial mass. This explains the main peak in BH XRB companion mass distribution at $\sim 1-1.2\,M_\odot$.

During stable mass transfer onto BH we assume that mass transfer is limited to Eddington critical rate ($\dot{M}_{\rm Edd} \approx 10^{-7}\,M_\odot\,{\rm yr}^{-1}$) therefore this system follows a fully conservative mass transfer mode. In such a case mass transfer from lower mass star to more massive BH leads to the orbital expansion. However, this is counter-balanced by combined angular momentum loss via GR and MB and the orbit decays. With the decreasing semi-major axis the strength of GR increases and the rotation of the donor speeds up increasing the strength of MB (Ivanova & Taam 2003). This leads to the increase in mass transfer rate ($\dot{M} \approx 10^{-10}-10^{-9}\,M_\odot\,{\rm yr}^{-1}$) when mass of the companion drops below $0.9-0.7\,M_\odot$ and separation decreases to $a = 2-3\,R_\odot$. This has two consequences. First, the donor mass depletion accelerates so the system contributes less and less to the companion mass distribution in the decreasing mass bins. We note the gradual decrease in number of systems leftward of $1\,M_\odot$. Second, for some systems the binary parameters are such that mass transfer may accelerate over $\dot{M}_{\rm disk}$ and system becomes a persistent XRB causing further depletion in our distribution as only transient mass distribution is of interest here (the observations shown in Figure 1 include only transient BH XRBs). The intensive mass transfer rather quickly (0.5 Gyr) depletes donor mass below $0.35\,M_\odot$ and at this point the star becomes fully convective and MB turns off. Mass transfer slows down ($\dot{M} \approx 5 \times 10^{-11}\,M_\odot\,{\rm yr}^{-1}$) and donor mass slowly drops down to hydrogen burning limit ($\sim 0.1\,M_\odot$) when we stop calculations. This last phase lasts $\sim 1-2$ Gyr and due to slow evolution in mass transfer these systems form a secondary peak in donor mass distribution at $0.2\,M_\odot$. Note that mass transfer rates calculated with our population synthesis code `StarTrack` are in agreement with ones inferred from obser-

vations. For example, the mass transfer rates for BH transients were estimated at the level of $\gtrsim 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$ by King (1988) and $\sim 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$ by Justham et al. (2006).

Systems with secondaries of lower mass than in the above example follow very similar evolution. They enter the mass distribution at lower mass and move across it in a similar fashion as we assume effective de-rejuvenation of mass losing stars. The parameters (i.e., radius and luminosity setting mass transfer rate) of a star that is $0.9\,\mathrm{M_\odot}$ and on main sequence are not drastically different whether this star was born with $0.9\,\mathrm{M_\odot}$ or was born as $1.1\,\mathrm{M_\odot}$ star and then reduced to $0.9\,\mathrm{M_\odot}$ by RLOF (Hurley et al. 2000).

Systems with higher mass secondaries evolve quite differently than in the above example. Primary is more massive than $\sim 40\,\mathrm{M_\odot}$, while secondary is typically $\sim 3-4\,\mathrm{M_\odot}$ star. Rapid evolution of primary leads to the CE while it is core He burning. After significant orbital decay, the close binary emerges out of CE. Massive He core collapses to form a $\sim 10\,\mathrm{M_\odot}$ BH at about $5\,\mathrm{Myr}$ since ZAMS. For such a massive star we assume the direct BH formation with no supernova explosion. The companion initiates RLOF during its main sequence evolution due to its nuclear expansion and GR emission at $\sim 100\,\mathrm{Myr}$. Stable mass transfer from a rather massive main sequence (MS) star begins removing mass from the secondary at moderate rate ($\dot{M} \approx 5 \times 10^{-9}\,\mathrm{M_\odot\,yr^{-1}}$). System appears as transient XRB at this phase. During this phase orbital separation increases from $a = 4\,\mathrm{R_\odot}$ to $a = 5\,\mathrm{R_\odot}$ (conservative mass transfer from less massive to more massive binary component, with no intervening MB). This phase lasts for $\sim 1-2\,\mathrm{Gyr}$ until the donor becomes low mass MS star ($M_b < 1.25\,\mathrm{M_\odot}$) and develops a convective envelope. Since mass transfer rate is rather constant during this phase the resulting mass distribution is flat above $1.25\,\mathrm{M_\odot}$. Below this mass the donor is a subject to MB and mass transfer significantly increases ($\dot{M} \approx 2.5 \times 10^{-7}\,\mathrm{M_\odot\,yr^{-1}}$). This phase lasts only about $1\,\mathrm{Myr}$ but donor drops in mass to $M_b = 1\,\mathrm{M_\odot}$ and becomes a HG star. Orbit has expanded (high mass transfer rate wins over MB and GR) to $a = 7\,\mathrm{R_\odot}$. At this short phase the system becomes a persistent XRB and disappears from our population of interest. These systems do not contribute to the main peak of the distribution. A HG star, that has formed from de-rejuvenated $3-4\,\mathrm{M_\odot}$ MS star, has temperature above $\sim 5000\,K$ and has most likely radiative envelope (e.g., Belczynski et al. (2008)). For such a star MB turns off and mass transfer slows significantly down ($\dot{M} \approx 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$). The system re-appears as transient on the left side of the main peak. At lower mass ($M_b \lesssim 0.9-0.8\,\mathrm{M_\odot}$) donor becomes red giant with convective envelope, MB turns on again increasing mass transfer rate ($\dot{M} \approx 10^{-9}\,\mathrm{M_\odot\,yr^{-1}}$). The combined effects of MB and GR overcome such moderate mass transfer rate and lead to a decrease of orbital separation. On the other hand, mass loss from convective red giant envelope along with its evolutionary expansion leads to donor's radius increase and when donor's radius exceeds its Roche lobe radius by factor of 2 we stop calculations.

Our condition to terminate calculations is somewhat arbitrary. In one alternative simulation we have relaxed this condition. MB (convective red giant) and GR (very close system $a \sim 3-4\,\mathrm{R_\odot}$) decrease the semi-major axis. At the same time, a low mass red giant donor ($M_b \sim 0.6\,\mathrm{M_\odot}$) responds with expansion to mass loss. Therefore, we have a runaway situation that in a short time leads to a CE and termination of BHXRT phase.

3.3. *Enthalpy model*

Figure 2 shows the predicted companion mass distribution for increased λ value ($f_\lambda = 5$). The distribution is very similar in shape to standard model distribution with main peak at $\sim 1\,\mathrm{M_\odot}$ and secondary peak at $\sim 0.2\,\mathrm{M_\odot}$. Despite the expectation to form BHXRTs with lower mass companions (due to easier envelope ejection) we do not find significant improvement. The predicted companion mass distribution is still in tension with the available observations.

We also note the increase in number of BHXRTs in this model as compared to the standard model. This is the combined result of initial distribution of binary separations and CE filtering. We start with the (statistically) same population of binaries in each model. For a given system to become a BHXRT a very specific post-CE separation is required ($a \sim 5-10\,\mathrm{R_\odot}$). It means that for similar binary component masses in the standard model pre-CE (and thus initial ZAMS) separation is larger than in the enthalpy model (in which the envelope binding energy is smaller). In each model there is more binaries with small separations as compared to number of systems with large separations. Initial separations are drawn from distribution flat in logarithm ($\propto 1/a$).

The obvious counter-argument to the above reasoning follows from the IMF. There are more low mass stars (i.e. $0.5-0.7\,\mathrm{M_\odot}$) forming the peak of observed distribution than high mass stars produced in the peak of our model distributions ($1-1.2\,\mathrm{M_\odot}$). There are three major counter-acting factors to the IMF argument.

(i) Stars below $1\,\mathrm{M_\odot}$ almost do not expand within Hubble time. It means that the range of post-CE separations is rather narrow for the system with such low mass companion to later enter RLOF and become BHXRT. The onset of RLOF is further hindered by the small mass of one component (donor) that leads to less efficient orbital angular momentum loss via GR and MB.

(ii) As in standard model (main example of evolution) systems with main sequence donors below $1\,\mathrm{M_\odot}$ evolve relatively quickly toward very low mass therefore their contribution to the companion mass distribution of BHXRTs is small. The rapid evolution follows from high mass transfer rates caused by combined effects of GR and MB enhanced by small separations required for this low mass donors to fill their Roche lobes.

(iii) It happens that in the low mass regime of donor mass where the observational peak appears some of our synthetic systems are found to be persistent XRBs. Below we give example of such evolutionary scenario in the enthalpy model framework.

A binary after forming a BH ($8\,\mathrm{M_\odot}$) enters a RLOF with a $\sim 1\,\mathrm{M_\odot}$ donor at separation of $a = 5\,\mathrm{R_\odot}$. The mass transfer is driven by GR and MB for about $1-2\,\mathrm{Gyr}$ at low rate ($\dot{M} \approx 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$) producing a transient behavior. In this time the mass of a donor changes slowly (the peak in the companion mass distribution $\sim 1\,\mathrm{M_\odot}$). With mass transfer the orbit continuously decreases and once it is significantly reduced ($a \sim 2-3\,\mathrm{R_\odot}$) the mass transfer rate increases and the system leaves the peak and moves to the left in the mass distribution. Once mass of the donor drops below $\sim 0.7-0.6\,\mathrm{M_\odot}$ the mass transfer rate ($\dot{M} \gtrsim 5 \times 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$) exceeds the critical rate for disk instability and the binary becomes a persistent XRB. Within short time ($\sim 0.5\,\mathrm{Gyr}$) the donor loses most of its mass and its evolution becomes irrelevant.

3.4. *Angular momentum model*

The companion mass distribution of Galactic BHXRT obtained with CE prescription based on angular momentum conservation (Nelemans et al. 2000) differs significantly from the one calculated with the standard model (see Figure 3). The distribution is basically flat with most systems distributed in mass range $0.5 - 1.3\,M_\odot$ with a tail extending to higher masses. There is also a notable (by a factor of ~ 10) decrease in number of predicted BHXRTs.

The initial evolution of binaries that enter BHXRT phase is vary similar to the one in the standard model. The differences appear after CE phase. Systems emerging from CE are much wider ($a \sim 50\,R_\odot$) than in standard model ($a \sim 5 - 10\,R_\odot$). At such distances GR is not effective in orbital decay. The combined action of MB (donors below $1.25\,M_\odot$) and nuclear evolution are required to bring companions to RLOF over a long period of time ($\sim 5 - 10\,\text{Gyr}$). Relatively small expansion on MS (factor of ~ 2) is not effective enough. Only increased expansion on red giant branch (RGB) can initiate RLOF and X-ray binary phase. Only when the orbit is reduced to about half its size by MB, a RGB donor starts RLOF. The mass transfer rate is rather constant ($\dot{M} \approx 10^{-8}\,M_\odot\,\text{yr}^{-1}$) as a RGB star properties depend primarily on its core mass ($\sim 0.35\,M_\odot$) and not on its entire mass that decreases from $\sim 1 - 1.2\,M_\odot$ down to its core mass. That explains rather flat companion mass distribution over wide range of masses.

The very low BHXRT numbers in this model are the result of our assumption on the outcome of CE with HG donors. Since this model provides only moderate orbital contraction during CE the preference is given to systems that enter the CE at the smallest orbital separation. The massive stars that form BHs in our simulations evolve from MS to HG and then directly to core helium burning (CHeB) expanding at each phase. We do not allow for survival of CE phase for MS and HG donors due to potential lack of clear core-envelope structure (Belczynski et al. 2007). Only binaries with wide orbits that do not allow for RLOF before CHeB may survive CE phase and form BHXRT. In this model only a small fraction of binaries that at the very beginning of CHeB (the smallest allowed separations) initiate CE can produce post-CE orbits small enough that BHXRT is formed within Hubble time. In comparison, for the standard model evolution with more efficient CE orbital contraction more binaries (over a wider range of separations) can produce BHXRTs.

3.5. *Enhanced mass transfer model*

This model companion mass distribution shows the closest resemblance to the observed distribution. We note a well defined peak at companion mass $\sim 0.4\,M_\odot$ (see Figure 4). In this model we have increased mass transfer rate as to shift the standard model peak of companion mass from around $\sim 1\,M_\odot$ toward lower, observed, values. It may appear that we have quite successfully reproduced the observations (peak at $\sim 0.6\,M_\odot$). However, this is not the case.

So far we have not directly commented on the associated BH mass distribution of BHXRTs. In all previously discussed models BH masses were found in $5 - 15\,M_\odot$ range. This range is in agreement with the existence of mass gap and consistent with masses of BHs in the Galactic binaries (Belczynski et al. 2012b). In this model we find that majority of BHs have mass around $\sim 3\,M_\odot$. This finding is inconsistent with the observations. A potential observational bias that may lead to an overestimate of BH mass was proposed by Kreidberg et al.

(2012). However, it is hard to imagine that currently known wide spectrum of BH masses would be shifted to a very narrow range with peak at $\sim 3\,M_\odot$.

Due to increased mass transfer the BHs in this model form primarily from (more numerous) NSs via accretion induced collapse (AIC). The typical evolution of such system is briefly described below.

At ZAMS a binary consists of $\sim 20\,M_\odot$ and $\sim 4\,M_\odot$ stars. Primary evolves quickly and initiates a CE (post-CE separation $a = 30\,R_\odot$) and then forms a massive NS: $1.8\,M_\odot$. At some point the mass transfer from a companion onto a NS begins. At first the mass transfer rate ($\dot{M} \approx 10^{-5}\,M_\odot\,\text{yr}^{-1}$) proceeds over critical Eddington rate ($dM_{edd} = 1.7 \times 10^{-8}$) and most of the mass leaves the binary. As donor mass decreases, the mass transfer slows down ($\dot{M} \approx 10^{-8}\,M_\odot\,\text{yr}^{-1}$) and continues fully conservatively for a prolonged time (about few Gyr). During this phase the accreting object reaches our adopted maximum NS mass $M_{max,NS} = 3.0\,M_\odot$. At this point we assume that the NS collapses to become a BH. BH keeps accreting mass from the companion to reach $\gtrsim 3\,M_\odot$. After a compact object becomes a BH, companion mass changes from about $0.7\,M_\odot$ to $0.35\,M_\odot$ producing the peak in the mass distribution.

In Figure 4 we show results of calculation for the mass transfer rate increase by factor of $f_{ill} = 5$. No qualitative changes (in respect to BH mass distribution) are found for smaller ($f_{ill} = 2$) and larger ($f_{ill} = 10$) increase factors that we have tested.

3.6. *Importance of maximum NS mass*

The calculations presented above for different models employed maximum NS mass of $M_{max,NS} = 3\,M_\odot$ (see Section 2.1). In this model we lower this limit to $M_{max,NS} = 2\,M_\odot$ and the resulting companion mass distribution is presented in Figure 5. The distribution shows a very prominent peak at $\sim 1.4\,M_\odot$ with a minimum around the locus of observational distribution maximum ($\sim 0.5\,M_\odot$).

In this model we encounter the very similar situation as in the enhanced mass transfer rate model. Although the mass transfer is not increased, we have lowered the mass limit for BH formation. It allows some NSs in accreting binary systems to increase their mass just above $2\,M_\odot$, collapse to a BHs and become BHXRTs. Since the typical companion mass is around $\sim 1 - 3\,M_\odot$ there is just enough mass reservoir to build up BH mass to $3 - 5\,M_\odot$. This disagrees with the observed BH mass distribution ($M_{BH} \sim 5 - 15\,M_\odot$) for the Galactic BHXRTs. We can exclude this model based on the disagreement of the predicted BH and companion mass distributions with observations. Below we give a brief description of the typical evolution of the system in this model.

Initial progenitor binaries are qualitatively very different than in the standard model. Typical system consists of $\sim 20\,M_\odot$ primary and $\sim 2 - 3\,M_\odot$ secondary. At 10Myr since ZAMS, after CE and supernova explosion a highly eccentric binary forms ($a = 70\,R_\odot$, $e = 0.9$) with a relatively heavy NS ($M_{NS} \sim 1.7\,M_\odot$). Tidal forces are rather ineffective for stars with radiative envelopes (e.g., Claret (2007)) and it is not expected that such a binary will circularize before the secondary star overflows its Roche lobe (nuclear expansion on MS) at periastron passages. This happens at about 100Myr after the supernova explosion and we circularize the binary at periastron distance ($a = 7\,R_\odot$, $e = 0$). The mass ejected from the secondary at periastron passages must put some drag on a com-

panion and lead to gradual circularization (however see Sepin-sky et al. (2010)). The system starts its evolution through a RLOF. First, we encounter a phase of thermal-timescale RLOF ($\dot{M} \approx 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$) and then the mass transfer quickly slows down and allows for steady accretion onto NS at moderate rates ($\dot{M} \approx 10^{-8} - 10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$). At about 1 Gyr NS goes through AIC and forms a low mass BH ($M_{\mathrm{BH}} = 2\,M_\odot$). Companion mass is at that point reduced to $1-2\,M_\odot$ and system appears at BHXRT with moderate-to-low mass transfer rate ($\dot{M} \approx 10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$) and on very close orbit ($a \sim 4-5\,R_\odot$). As mass transfer continues to remove mass from the donor, MB turns on and this combined with increasing strength of GR ($a \sim 3\,R_\odot$) leads to further orbital decay. At the same time the donor evolves beyond MS and its radius increases. This leads to unstable situation and most likely the merger of the two stars. We stop calculations when donor radius exceeds its Roche lobe radius by factor of 2 at ~ 2 Gyr since ZAMS.

3.7. *Other factors*

Besides modifications to the input physics described above we have tried to alter several assumptions and employed laws/formulas that are important in modeling of Galactic BHXRTs. Below, we list the additional tests that we have performed.

We have employed two other prescriptions for magnetic braking, with (Andronov et al. 2003) and without (Rappaport et al. 1983) saturation of magnetic dynamo. Along the similar lines we have narrowed down the appearance of convective envelopes for MS stars from $0.35 - 1.25\,M_\odot$ to $0.35 - 0.9\,M_\odot$, thus suppressing the action of MB for stars in the main peak of most predicted companion mass distributions. In several models we have exchanged our assumption on continuous star formation rate in Galaxy with other prescriptions in order to assess the influence of BHXRT lifetime on the companion mass distribution. We have assumed that entire Galactic star formation was contained within 1 Gyr burst and we have positioned the burst at four different times beginning at 10, 9, 2, 1 Gyr ago. Then we have assumed that star formation was linear function of time. In one model we have assumed that star formation starts 10 Gyr ago at such value that it drops down to zero at present. In the other we have assumed that it starts 10 Gyr ago at zero and at present increases to its maximal value. All models were normalized in such a fashion as to obtain total stellar mass of $3 \times 10^{10}\,M_\odot$ formed over entire 10 Gyr of the Galactic disk evolution. None of the calculated companion mass distributions found in above simulations resembled the observed distribution of donor mass in Galactic BHXRTs.

We have changed parameters in `StarTrack` to make it more similar to the `SeBa` population synthesis code described in Portegies Zwart & Verbunt (1996) with later updates in Portegies Zwart & Yungelson (1998), Nelemans et al. (2001) and Nelemans et al. (2004). In particular, we have extended mass range for MS stars for which MB operates with to 0.3–1.6 $M_\odot$, for common envelope we have used energy balance with constant $\alpha \times \lambda = 2$, primary initial mass range was narrowed down to 25–100 $M_\odot$, while secondary mass down to 0.08–100 $M_\odot$ and we have adopted slightly higher natal kicks for neutron stars (Maxwellian with $\sigma = 300$ km s^{-1}). BH kicks are obtained by scaling down NS kicks. The rest of the parameters are the same as in our standard model calculation. This model is similar to the calculations of Yungelson et al. (2006) and we show the resulting donor mass distribution in Figure 6.

There is a slight improvement with the peak of distribution now at $\sim 0.9\,M_\odot$ and higher number of BH transients than found in our standard calculation. This is a direct result of adopting 40-times higher CE efficiency ($\alpha \times \lambda = 2$) as compared to our standard calculation ($\alpha \times \lambda = 0.05$).

In next step, we employed the same modification to our standard model as described above and we additionally follow Yungelson & Lasota (2008) suggestion and (totally) suppress magnetic braking during the ongoing RLOF. The results are shown in Figure 6. The peak of donor mass distribution is now found at $\sim 0.5 - 0.6\,M_\odot$, very close to where the observed peak appears ($\sim 0.5 - 0.7\,M_\odot$). Since suppression of MB extends the lifetime of BH transients, we also find many more systems in this model as compared to our standard calculation.

Systems that are found in the peak of donor mass distribution ($\sim 0.5 - 0.6\,M_\odot$) form from massive primaries and secondaries within initial mass range $\sim 0.8 - 1.25\,M_\odot$. After CE and BH formation, the orbital separation decreases due to combined action of MB and GR. Typically after several Gyr the secondary begins RLOF. We then suppress MB and the rate of angular momentum loss is significantly reduced. Companion slowly reduces its mass and with decreasing mass the mass transfer slows down. During the Hubble time, the star seldom falls below the $\sim 0.5\,M_\odot$. Stars with masses lower than $0.8\,M_\odot$ on ZAMS rarely have enough orbital energy to eject the envelope of massive primary and survive CE phase. Stars heavier that $\sim 1.6\,M_\odot$ are not subject to MB thus the secondary needs to finish CE very close to primary to be brought to RLOF by GR alone. As a result, the range of possible pre-CE separations is more restricted, which leads to lower formation probability of systems with donor mass over the MB threshold.

There is an additional population present in this model (see dashed line in Figure 6 marking systems with typical donor mass $\sim 0.1\,M_\odot$). As it appears there is a significant population of systems with light compact objects $\sim 2 - 3\,M_\odot$ and very low-mass companions. These systems form at first heavy NS ($1.6 - 1.9\,M_\odot$) that later during RLOF from a relatively massive companion ($1.5 - 1.7\,M_\odot$) collapses via AIC to become a light BH. If MB was not suppressed during RLOF then NS would not have accreted enough mass to become a BH as the two stars would very quickly merge due to very effective angular momentum loss. Since transients does not seem to host light BHs then, within the framework of our model, this result indicates that MB is not suppressed during RLOF. The assumption on MB suppression is further disapproved by recent observations of XTE J1118+480 and A0620-00 and they very rapid orbital period decay indicating very strong MB for close RLOF BH transients (González Hernández et al. 2014). Finally, in our opinion, this model involves unrealistically high CE efficiency ($\alpha = 40$; if the physical estimates of binding energy *lambda* = 0.05 is used).

4. SELECTION EFFECTS ON THE X-RAY BINARY POPULATION

Given that there are some disagreements between all of the theoretical models here and the observed distribution of X-ray binaries, some discussion of the selection effects for BH X-ray binaries is necessary. For objects to appear in the sample of 19 dynamically confirmed stellar mass BHs, they must meet two key criteria: (1) they must be detected in the X-rays and (2) they must have optical or infrared counterparts bright enough and in regions of low enough crowding that their mass functions can be measured.

The first criterion may be the source of the lack of objects with very low mass donor stars. Low mass donor stars will necessarily be main sequence stars (or degenerate low mass objects). Given the period-mass relation for Roche lobe overflowing objects (see Knigge et al. (2011) for the most up-to-date discussion of this relation), donor stars of $0.2\,M_\odot$ should overflow their Roche lobe in systems with orbital period of about 2 hours.

A correlation between the peak X-ray luminosity of an X-ray transient and the orbital period of the transient has been well established in recent years (Shahbaz et al. (1998); Portegies Zwart et al. (2004); Wu et al. (2010)). At the shortest orbital periods, the peak accretion rates will be well below the threshold of a few percent of the Eddington rate where BH X-ray binaries enter the high soft state (Maccarone 2003). As a result, the systems are likely to be in advection dominated states, with two consequences – first that the accretion will be radiatively inefficient, reducing the bolometric luminosity, and second that the X-ray spectrum will peak at 100-200 keV, rather than at a few keV, meaning that the most sensitive all-sky monitors, which have traditionally operated below 15 keV, will not catch the peak of the X-ray spectrum. Maccarone & Patruno (2013) noted that these objects might manifest themselves as "very faint X-ray transients", while Knevitt et al. (2013) have discussed how these objects might be absent in existing catalogs of X-ray binaries for similar reasons. It is worth noting that in recent years, a few objects have been discovered that are strong (but not yet dynamically confirmed) BH candidates, and which have orbital periods less than 4 hours – Swift J1753.5-1027 (Zurita et al. 2008), and MAXI J1659-152 (Kuulkers et al. 2013), and these were both discovered by All-Sky Monitors much more sensitive than those which existed before Swift was launched. It is important to note, also, that selection effects on the basis of orbital period are much more likely to be important than selection effects on the basis of BH mass – see Özel et al. (2010) for a discussion of why the latter is, at most, a minor issue.

The second criterion is also a potentially serious issue, although how it may manifest itself is not entirely clear. This paper presents a study of 19 objects which are dynamically confirmed BH candidates. A slightly larger number of objects show strong albeit indirect evidence for being BHs (Remillard & McClintock 2006). These lines of evidence can include: systems showing an ultrasoft spectral component (White & Marshall 1984); showing a lack of Type I X-ray bursts despite having been well-studied (Remillard & McClintock 2006); and strong radio emission relative to the X-ray emission level (e.g. Strader et al. (2012) ; Chomiuk et al. (2013). In one case, that of 4U 1957+11, a system shows a range of indirect evidence for being a BH, but has remained as a persistently bright source since the Uhuru era, making it impossible for its donor star's light to be seen, and hence for its mass function to be estimated (e.g. Nowak et al. (2008); Russell et al. (2011)). In the two globular clusters, the crowding of the stars makes it difficult to measure the donor star's spectrum. In nearly all of the other cases, the systems are very close to the Galactic Plane, so that foreground extinction makes measurement of the donor stars' spectra impractical with current instrumentation. The effects of this criterion on the orbital period distribution of dynamically confirmed BH X-ray binaries have not yet been studied well enough to determine how it will manifest itself. It seems likely, though, that if there is a strong correlation between orbital period and natal kick velocity, that this

effect may be important – being kicked well out of the Galactic Plane makes optical follow-up much easier. An alternative to understanding the selection effects for outbursting sources will be to develop and understand a sample of quiescent BH X-ray binaries, one of the key goals of the Chandra Galactic Bulge Survey (Jonker et al. 2011).

5. CONCLUSIONS

We have reexamined the issue of donor mass in the Galactic BH X-ray transient binaries. Since the formation scenarios involve CE phase initiated by a massive BH progenitor, it is naturally expected that companion mass should not be too small as to avoid the CE merger. However, the donors that are found in Galactic BHXRTs have very low mass $\sim 0.6\,M_\odot$. Early studies have shown that stars with mass above $2\,M_\odot$ are the most likely companions for Galactic BHs. With the updated population synthesis code we have shown that stars with mass $1\,M_\odot$ are most likely companions. Despite the factor of ~ 2 improvement the predictions are still in tension with available observations.

We have implemented several alternatives and modifications in our evolutionary calculations to test whether it is possible to bring predictions closer to the observations. We have failed to reproduced the observed distribution of companion mass. The problem seems to be deeper than previously believed. Our results show that, in spite of the fact that common envelope phase seems necessary for decreasing the separation and, therefore, the formation of low mass X-ray binaries, it is not the crucial factor. This is demonstrated by comparison of two models; one with the standard CE ejection efficiency and one with the significantly increased efficiency (see Figure 2). There is no clear improvement in the position of the donor mass peak. Actually, both models show minimum at the locus of the observed companion mass peak ($\sim 0.6\,M_\odot$). The minimum found in almost all our models is a consequence of a donor size. For these very low masses the donor is small. To fill its Roche lobe a donor needs to be in a very close binary. The very small separation means strong binary angular momentum loss due to emission of gravitational radiation. It also sets the donor fast rotation (synchronization assumed during RLOF) leading to efficient magnetic braking. Both processes increase mass transfer rate and therefore low mass donors lose mass faster than higher mass stars. It means that the low mass stars from the observational peak ($\sim 0.6\,M_\odot$) are less likely to appear in the BH binary population than the higher mass stars, like the ones found in the predicted peak ($\sim 1\,M_\odot$). Additionally, some systems with these low mass donors disappear altogether as the high mass transfer rate stops the transient behavior.

There are two general types of solution to this persisting problem. Either the observed distribution of companion mass is heavily biased or the details of mass transfer for low mass stars are not understood.

There are several factors that may potentially bias the observed donor mass spectrum. There exists a potential bias in measurements of binary inclination in BH transients that may affect component mass estimates. However, the potentially underestimated inclinations (Kreidberg et al. 2012) would lead to a decrease in donor mass. There are clearly factors which can make systems with low mass donor stars harder to detect. There may also potentially exist a trend that makes systems with higher mass companions less visible. For example, for more massive donors with lower mass transfer rates it may take longer for the disk to refill after the out-

burst. It would produce longer duty cycle and thus decrease the probability of discovery as BH candidates are generally identified by outbursts. Finally, it is not well understood what effects natal kicks have on the difference between the intrinsic and observed donor mass distributions. Given that about half of the BH X-ray binaries are too heavily extincted to have their system parameters measured, this is clearly something that could potentially be important.

On the theoretical side the evolution through mass transfer for these extreme mass ratio systems with very low mass companions may not be fully understood. As the side effect of our main work, we found that the very evident problem is the lack of generally accepted magnetic braking model. More than that, it seems like all proposed models fail to explain (MB too weak) the recent observations of rapid orbital decay of XTE J1118+480 (González Hernández et al. 2013). Additionally, it is not clear whether the transient behavior can be estimated based only on the mass transfer rate (and how uncertain such estimates are) as the disk instability theory is far from being fully understood.

Besides various models for MB, with and without dynamo saturation, we applied significantly increased RLOF rates (by factor of ~ 10) as motivated by potential irradiation of donor by the accreting BH/disk. However, it may be also a proxy for increased MB operating for all our RLOF systems. We have also employed the idea put forward by Yungelson et al. (2006) and Yungelson & Lasota (2008) and we completely turned off MB for all RLOF systems. In both cases it was found that

donor mass in our predicted population of Galactic BH transients very closely resemble observations. However, the BH mass spectrum is totally different (mostly light $\sim 2-3\,\mathrm{M_\odot}$ BHs) than observed. It may very well indicate that more complex MB modification is required. Modification that not only alters the MB strength but that also most likely changes with properties of donor stars. It may be potentially possible to reverse engineer MB from donor mass observations, provided that the observations are not heavily biased. Any such attempt should take into account the available constraints from orbital decay measurements indicating that for very low mass RLOF donors ($\sim 0.2-0.4\,\mathrm{M_\odot}$) the MB is much stronger than any available model can predict.

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TABLE 1
PROPERTIES OF GALACTIC BLACK HOLE X-RAY BINARIES

No	Name	$M_{comp}[M_{\odot}]$[b]	Spec. type	$M_{BH}[M_{\odot}]$	P_{orb}	citations[e]
1	XTE J1118+480	0.22 ± 0.07	K7/M1V	$6.9 \div 8.2$	4.08	[1,17,17,38]
2	XTE J1550-564	0.3 ± 0.07	K2/4IV	10.5 ± 1.0	37	[2,2,28,2]
3	GS 2000+25	$0.16 \div 0.47(0.315)$	K3/6V	~ 6.55	8.26	[3,18,3,40]
4	GRO J0422+32	~ 0.45	M0/4V	~ 10.4	5.09	[4,19,4,4]
5	GRS 1009-45	~ 0.5	G5/K0V	~ 8.5	6.86 ± 0.12	[5,20,5,41]
6	GRS 1716-249	~ 1.6	K-M	$\gtrsim 4.9$	14.7	[37,37,37,37]
7	GX339-4	$0.3 \div 1.1(0.54)$	KIV	> 7	42	[6,21,6,21]
8	H1705-25	$0.15 \div 1.0$	K3/M0V	$4.9 \div 7.9$	12.55	[7,22,29,29]
9	A0620-00	0.68 ± 0.18	K2/7V	6.6 ± 0.25	7.75	[8,23,30,42]
10	XTEJ1650-50(0)	0.7	K4V	~ 5.1	7.63	[c,24,31,24]
11	XTEJ1859+226	0.7	K5V	7.7 ± 1.3	6.58 ± 0.05	[c,25,32,25]
12	GS2023+338	$0.5 \div 1.0(0.7)$	K0/3IV	12 ± 2	156	[9,26,33,43]
13	GRS 1124-68	$0.3 \div 2.5(0.8)$	K5V	6.95 ± 0.6	10.392	[10,10,34,44]
14	GRS1915+105	0.8 ± 0.5	K1/5III	12.9 ± 2.4	811.2 ± 2.4	[11,27,35,35]
15	GS 1354-64	1.03	G5IV	7.6 ± 0.7	61.07	[c,12,12,12]
16	GROJ1655-40	1.75 ± 0.25	F3/G0IV	5.31 ± 0.07	62.909 ± 0.003	[d,13,36,45]
17	4U1543-47	$2.3 \div 2.6(2.45)$	A2V	$2.7 \div 7.5$	26.8	[14,14,14,46]
18	XTEJ1819-254	$5.49 \div 8.14(6.81)$	B9III	$8.73 \div 11.70$	67.62	[15,15,38,15]
19	CygX-1 *persistent* [a]	19.2 ± 1.9	OI	14.8 ± 0.1	134.4	[16,16,16,16]

[a] Cyg X-1 is the only persistent Galactic source, other systems are transients

[b] When only a range of companion masses is available the value used to built the observational distribution (e.g., Figure 1) is given in parenthesis

[c] Derived from the spectral type

[d] Derived from $M_{BH} = 5.31 \pm 0.07$(Motta et al. 2014) and $q = 0.329 \pm 0.047$(González Hernández et al. 2008)

[e] Citations are organized as follows: [M_{comp},Spectral type,M_{BH},P_{orb}]. References: [1]González Hernández et al. (2012); [2]Orosz et al. (2011b); [3]Ioannou et al. (2004) ; [4]Reynolds et al. (2007); [5]Macias et al. (2011) ; [6]Muñoz-Darias et al. (2008) ; [7]Martin et al. (1995) ; [8]Gelino et al. (2001b) ; [9]Casares & Charles (1994); [10]Shahbaz et al. (1997); [11]Harlaftis & Greiner (2004) [12]Casares et al. (2009) ; [13]Beer & Podsiadlowski (2002) ; [14]Orosz et al. (1998) ; [15]Orosz et al. (2001) ; [16]Orosz et al. (2011a) ; [17]Khargharia et al. (2013); [18]Harlaftis et al. (1996); [19]Gelino & Harrison (2003); [20]della Valle et al. (1997); [21]Hynes et al. (2003); [22]Filippenko et al. (1997); [23]Froning et al. (2011); [24]Orosz et al. (2004) ; [25]Corral-Santana et al. (2011); [26]Khargharia et al. (2010); [27]Greiner et al. (2001); [28]Li et al. (2013) ; [29]Harlaftis et al. (1997); [30]Cantrell et al. (2010) ; [31]Slaný & Stuchlík (2008) ; [32]Shaposhnikov et al. (2009); [33]Shahbaz et al. (1994) ; [34]Gelino et al. (2001a) ; [35]Hurley et al. (2013) ; [36]Motta et al. (2014) ; [37]Masetti et al. (1996) ; [38]Martin et al. (2008); [39]Torres et al. (2004); [40]Chevalier & Ilovaisky (1990); [41]Shahbaz et al. (1996); [42]Johannsen et al. (2009); [43]Casares et al. (1992); [44]Orosz et al. (1996); [45]González Hernández et al. (2008); [46]Orosz et al. (2002);
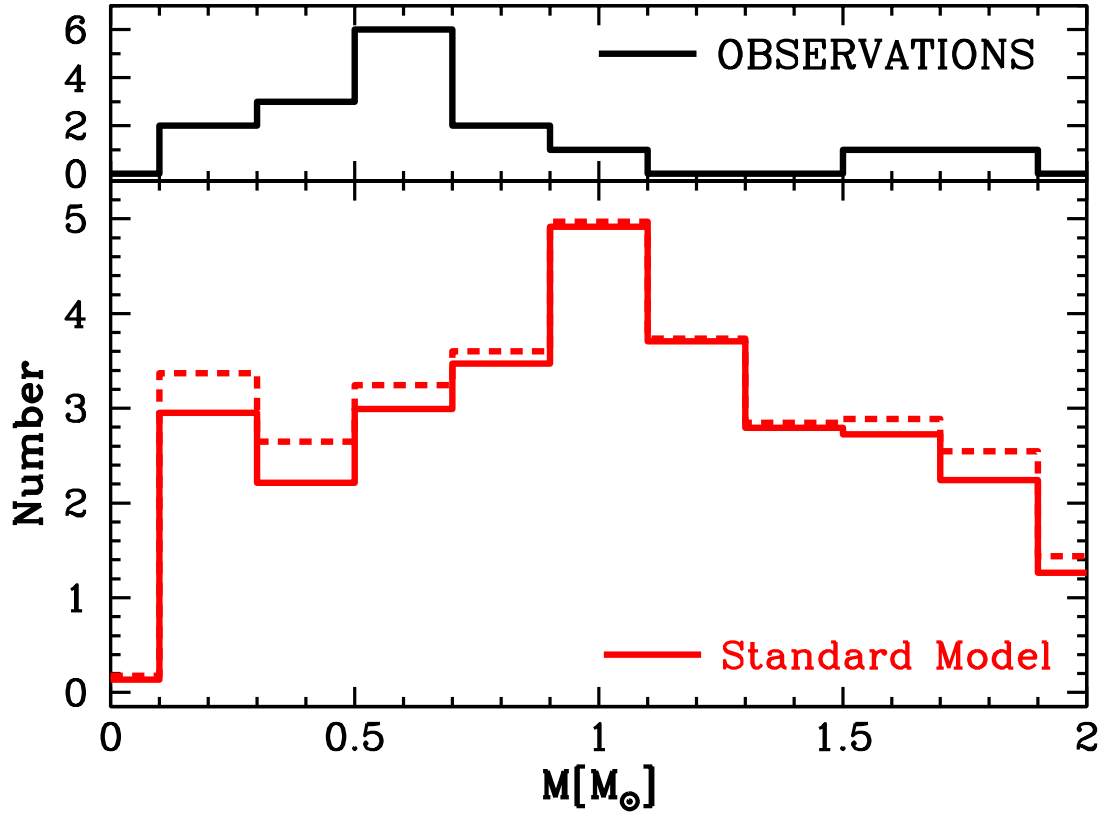
FIG. 1.— Top panel: observationally estimated donor masses for 16 Galactic BH transients with low mass companions. Bottom panel: distribution of donor mass for BH transient population obtained with our standard evolutionary scenario that employs energy balance for common envelope (see Section 2.2). Solid line shows predicted current Galactic population of BH transients, while dashed line shows both transient and persistent systems. We find about 30 systems in the mass range $0-2\,M_{\odot}$. Observations peak at $\sim 0.6\,M_{\odot}$, whereas the simulation peak at $\sim 1\,M_{\odot}$.
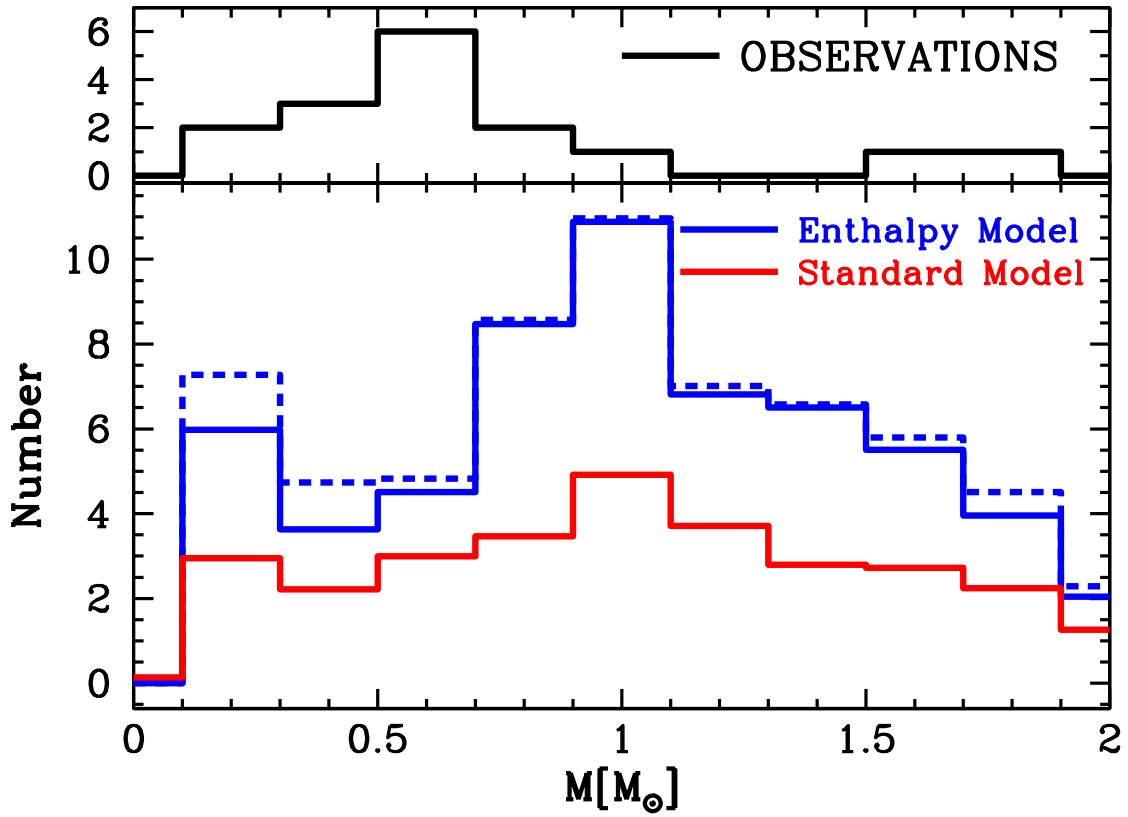
FIG. 2.— The donor mass distribution for evolution that incorporates the enthalpy common envelop model with much easier envelope ejection that assumed in the standard model. We find about 60 BH transients (solid line) with low mass companions in this model. The persistent systems are also marked as in Figure 1. The observations and standard model results are shown for comparison. Note that this model, despite the expectations, produces donors with a typical mass same as in standard model: $\sim 1\,M_\odot$. For explanation see Section 3.3.
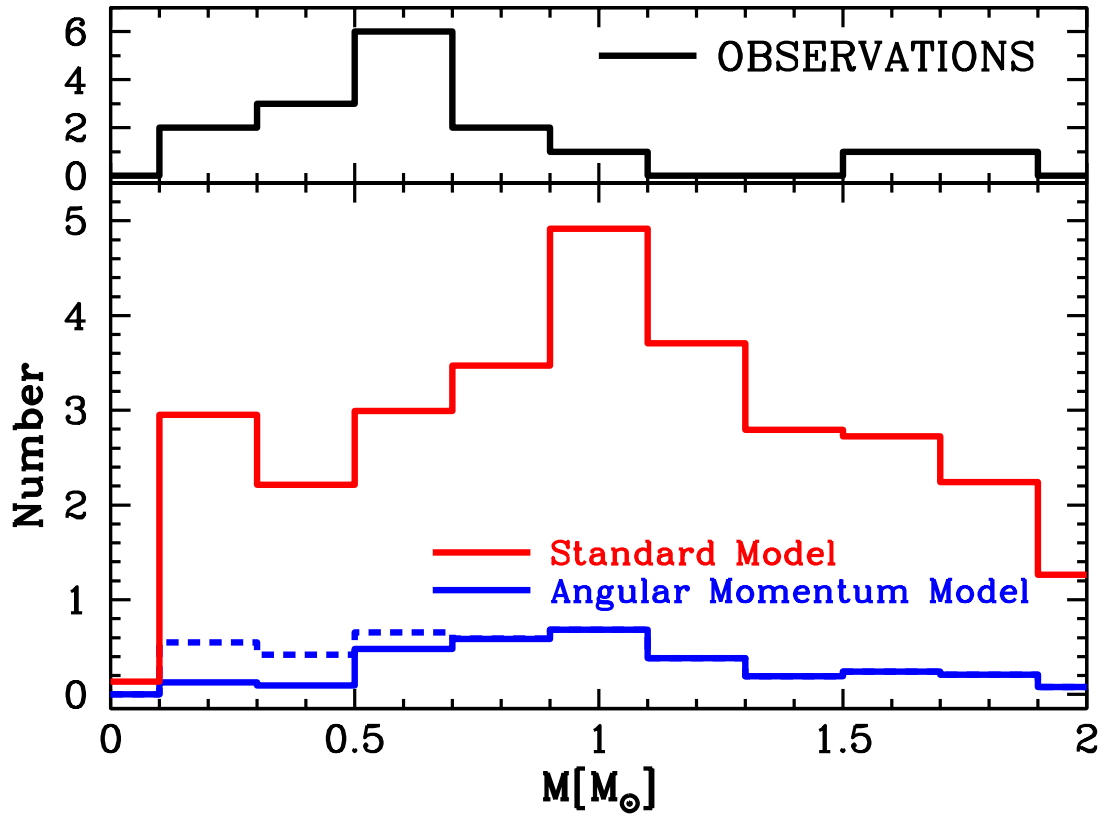
FIG. 3.— The distribution of donor mass in BH systems for an evolutionary scenario that employs angular momentum model of common envelope. Notation is the same as in previous figures. In this model we obtain only about 3 transient systems with low mass companions. Additionally, note that the predicted distribution does not resemble the observations.
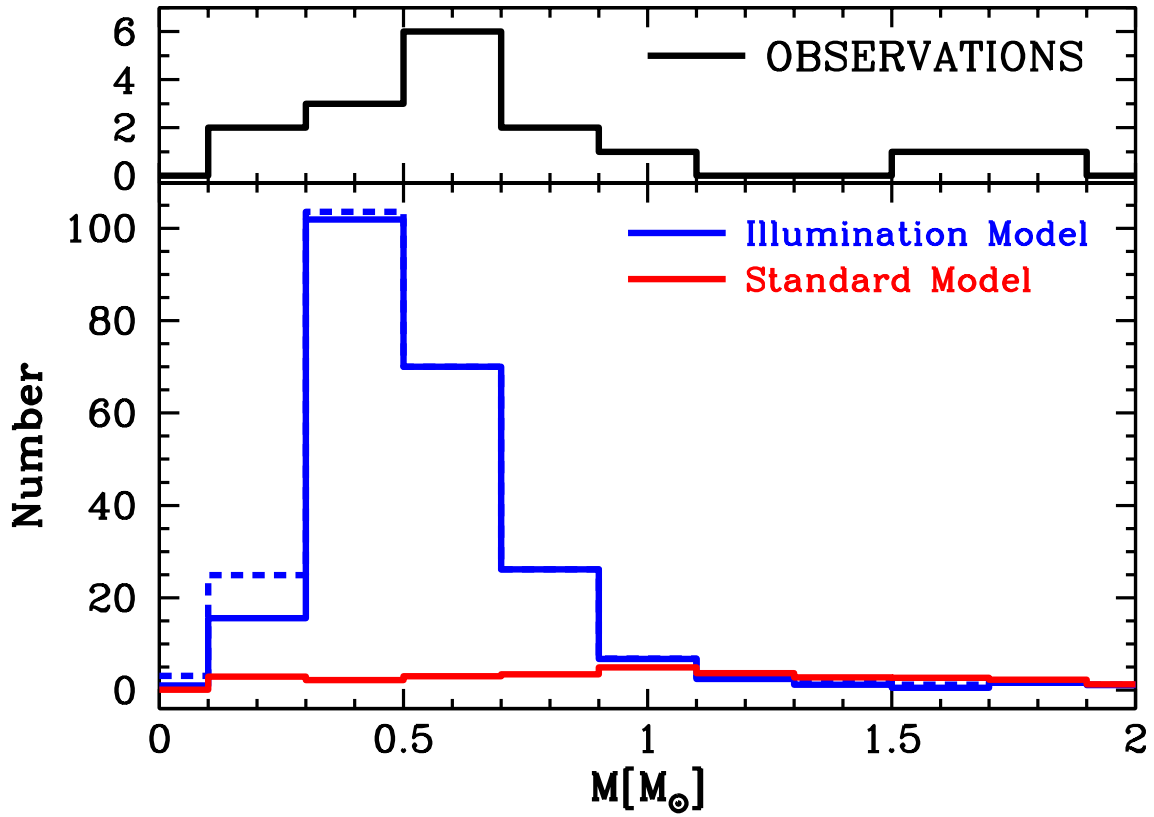
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Fig. 4.— The distribution of donor mass in BH systems for evolution with increased (by factor of $f_\lambda = 5$) mass transfer rate. The increase may be potentially caused by illumination of the companion by the accretion disk around BH. Note the large number of transient systems: ~ 230 and the fact that companion mass distribution peaks at $\sim 0.4\,M_\odot$. Despite the fact that predicted donor masses are rather close to the observed ones, this model is excluded based on the associated BH mass distribution. Majority of BHs in this model form via accretion induce collapse of heavy NSs and are found with mass just above $\sim 3\,M_\odot$. This excludes this model as Galactic BHs are found with mass $5-15\,M_\odot$. See Section 3.5 for more details. Notation is the same as in previous figures.
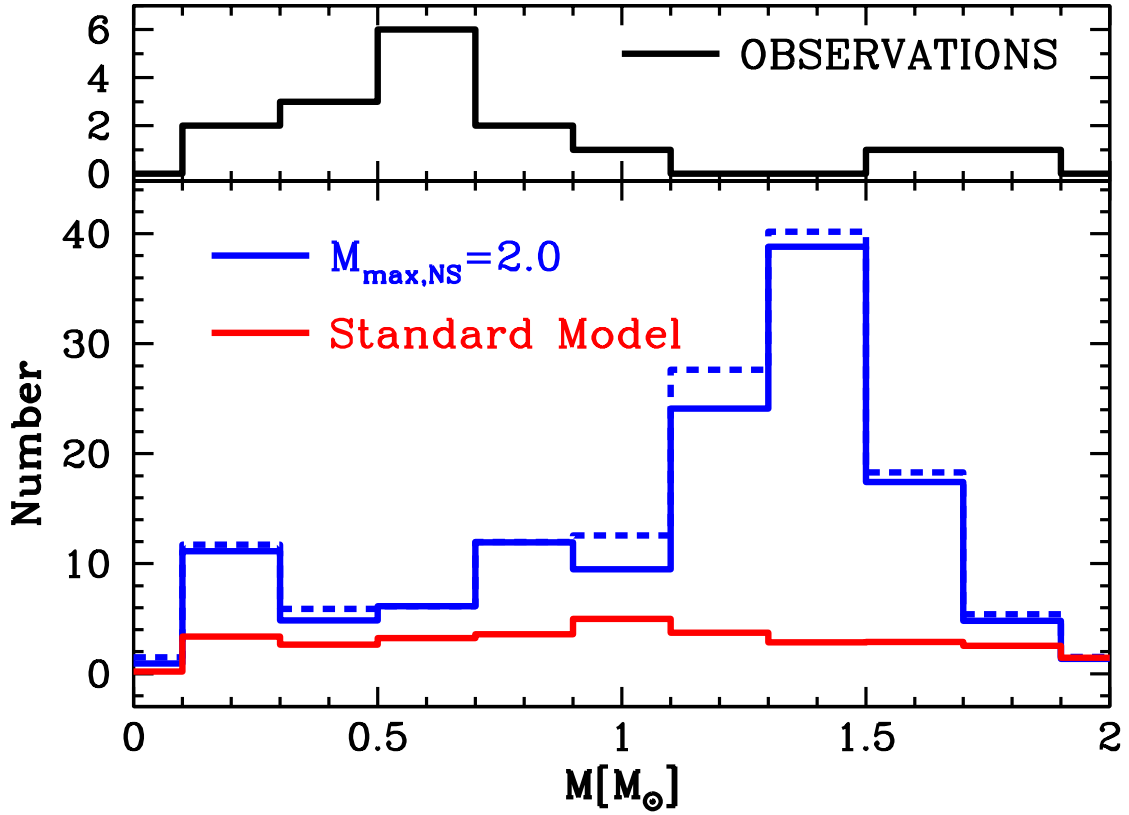
FIG. 5.— The distribution of donor mass in BH systems for evolution with decreased maximum NS mass: $M_{max,NS} = 2$. In all the other models we have employed a larger value $M_{max,NS} = 3$. Note the increased number of BH transients (~ 130) and shift of the distribution peak to $1.4 \, M_\odot$ as compared with the standard model. In this model we find majority of BHs with very low mass that have formed via accretion induced collapse. This and the shape of companion mass distribution render this model as very unlikely. For more information see Section 3.6. Notation is the same as in previous figures.
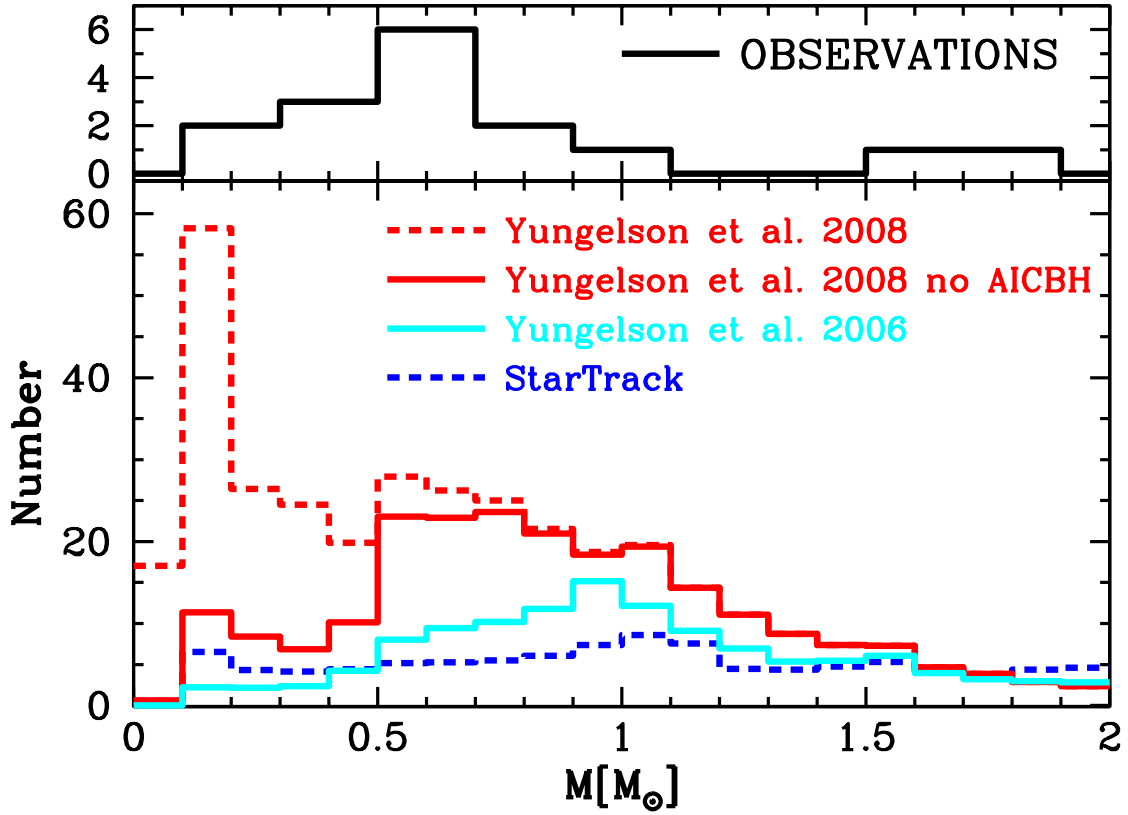
FIG. 6.— The distribution of donor mass in BH transient systems obtained whit the StarTrack model modified to resemble recent Seba calculations. Model marked as Yungelson et al. (2006) have very high CE ejection efficiency and extended initial donor mass range for MB to operate. In model denoted as Yungelson & Lasota (2008) we have additionally suppressed MB during ongoing RLOF. For this model we note the significant population of light BHs ($\sim 2-3\,\mathrm{M}_\odot$) formed through accretion induced collapse of NSs. Our standard StarTrack model is shown for comparison. See Section 3.7 for details.